Quantitative Analysis of Selected Land-Use Systems with Sunflower

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STATEMENTS

1. "Soil hydraulic conductivity equations contain a disturbing element of armchair speculation that hinders their use in the analysis of land use systems, particularly in arid and semi-arid regions".

(This thesis)

2. "Water retention curves based on traditional desorption measurements systematically overestimate water availability in a field situation".

(This thesis)

3. "The future of quantified land evaluation is dependent on progress in integrating the soil-plant-atmosphere continuum in dynamic simulation".

(This thesis)

4. "Many soil data that are routinely collected are unfit for use in dynamic simulation of land-use systems performance".

(This thesis)

5. "Indexing land qualities can be misleading: it is more telling to analyze processes than interpret lumped parameters".

(This thesis)

6. "Rather than to identify alternative land-use scenarios, land evaluation tries to emphasize that resources are limited".

(This thesis)

7. "There is no time to relax in the field of agriculture. Land is shrinking and biotic and abiotic stresses are increasing... While it is nice to have a vision about a common future, we should not forget that we do not have a common present".

(Swaminathan, 1989. In Borral Duvick, "Biotechnology and sustainable agriculture").

8. "Policy support models connect those who need support for their policy with those who need support for their models".

(a self justification)

These statements belong to the thesis "Quantitative Analysis of Selected Land-Use Systems with Sunflower". J. M. Cardoso de Barros, Wageningen, 19 March 1997.

ABSTRACT

Barros, J.M.C. de, 1996. Quantitative Analysis of Selected Land-Use systems with Sunflower. Doctoral thesis, Wageningen Agricultural University, Wageningen, The Netherlands. (viii) + 169 p, 65 tbs, 67 figs, 4 annexes (on diskette), 62 refs, English and Dutch summaries.

Land-use systems with sunflower were quantified using a dynamic crop-growth simulation model for calculating the biophysical production potential and water-limited production potential.

Crop data were collected in 1993 and 1994 in field experiments with three varieties of sunflower and three water regimes at Coria del Rio, Andalusia, Spain. Soil and weather conditions were monitored.

The output of the calculations are potential yield and production; they reflect the effects of soil and weather conditions during the growing season for Land Utilization Types with defined crop characteristics and management activities.

The evaluation of crop performance with weather data of many years reveals the long-term success of specific land use systems and the risk of crop failure in rainfed agriculture.

Land suitability is established by matching land use requirements with the compounded land qualities and land characteristics. Sustainability is achieved by adapting the use of inputs or by changing the land use requirements (changing the crop/variety) to fit the actual land characteristics and land qualities.

Quantified land-use system evaluation is a point analysis. The basic spatial unit is defined by the scale of the evaluation exercise, i.e. by the resolution of data on the environmental conditions, the soil properties, the crop characteristics and the management applied. A set of point analyses, with their variabilities, over a number of years may be processed by a geographic information system to yield a regional suitability map for a specific land use.

Additional index words: (quantified) land evaluation, land-use systems, sunflower, *Helianthus annuus*, simulation model, dry matter distribution, phenology, assimilation, evapotranspiration, water balance, nutrient requirements.

PREFACE

During my M.Sc. course in Soil and Water at the Wageningen Agricultural University, I became acquainted with simulation of crop growth. It was amazing that crops could be "grown" in the computer in a wide array of production situation scenarios. Unintentionally, I strayed away from my original specialisation in irrigation to theoretical production ecology and quantified land evaluation.

Like many people, I had the idea that computer simulation programs ask for large amounts of data which are only readily available on few advanced research stations. And that the generated output would only apply to a controlled environment. And how could one check the validity and sense of generated results? That determined the subject of this thesis: the challenge to perform a quantified land evaluation with the minimal input data and with proper validation of the output.

The crop/commodity "sunflower" was chosen by the Institute of Natural Resources and Agrobiology of Seville, Spain; it is one of the main crops of Andalusia. With its experience in statistical/parametric models of crop production, the Institute was keen to extend its research into dynamic modelling. The field research was done in 1993 and 1994 on the experimental farm of the Institute at Coria del Rio, 15 kilometres from Seville. It was hard work, monitoring crop growth by recurrent partial harvestings and sampling of soil and crop. I am grateful to Manolo Fernandez and Fernando Sanchez for their daily support and friendship. They helped when and where they could to make field experimentation a success. I also got help from two enthusiastic students: Miguel Gimenez in 1993 and Janjo de Haan in 1994, who assisted with me their practical work. Their company was also highly appreciated.

I thank Johan Bouma for "welcoming me aboard" and Diego de la Rosa for the chance to do the field research at his Institute. My supervisor was Paul Driessen. I profoundly appreciate his enthusiasm to share his knowledge and wisdom, and the endless discussions and time spent with me. And also his humour.

I am deeply indebted to the Dutch Government for providing my (NUFFIC) scholarship. The field research costs were shared with the Institute in Seville.

This thesis could not have been completed without the cooperation, assistance and support of many persons. Among others the staff of the Department of Soil Science and Geology (notably Piet Peters, Nico Konijn and Marcel Lubbers) and the staff of the Institute in Seville (José Mudarra, Paco Pelegrin, Juan Cornejo, Rafael Lopez, Joep Crompvoets and Enrique Fernandez). I thank Adrie Jacobs (Department of Meteorology) and Walter Rossing (Department of Theoretical Production Ecology) for reviewing parts of this thesis, and Jacquelijn Ringersma (Department of Irrigation) for lending me her field equipment. Special thanks are due to Ruud Jordens who pushed me into this adventure.

Many others are not listed but I am gratiful to them all! In the same way I would appreciate if my work would be of interest and useful to others.

CONTENTS

LIST OF SYMBOLS

ABSRAD	actual quantity of absorbed radiation ($J.m^{-2}.d^{-1}$)
AirDen	air density at T24h ($kg.m^{-3}$)
AirPres	air pressure at T24h (mbar)
AK	texture-specific empirical constant ($cm^{-2.4}.d^{-1}$)
AlbdCrop	sunflower albedo (0.25)
AlbdGrass	grass albedo (0.23)
AlbdSoil	bare soil albedo (0.15)
AlbdWater	water albedo (0.06)
ALFA	texture-specific geometry constant (cm^{-1})
ALT	altitude of the site (m)
AMAX	maximum rate of assimilation at actual temperature ($kg.ha^{-1}.d^{-1}$)
Ampl	daily temperature amplitude (°C)
ASSC	actual surface storage capacity (cm)
Assim	gross rate of CO_2 reduction by closed reference crop ($kg.ha^{-1}.d^{-1}$)
AUXIL	air heat capacity ($J.m^{-3}.K^{-1}$)
Boltz	Stephan-Boltzmann constant (0.0049 $J.m^{-2}.d^{-1}.K^{-4}$)
BU	base uptake of nutrients ($kg.ha^{-1}$)
C3C4$	label for C3 or C4 photosynthetic pathway
CANRAD	total radiation at canopy level ($J.m^{-2}.s^{-1}$)
CCOS	cosine of latitude
CF	conversion factor
CFLEAF	correction factor for actual soil coverage (-)
CFTEMP	correction factor for actual daily temperature (-)
CFWATER	correction factor for actual availability of water (-)
CH	crop height (m)
CR	rate of capillary rise ($cm.d^{-1}$)
Croplabel$	crop (variety) name
CY	yield from unfertilized field ($kg.ha^{-1}$)
D	rate of deep percolation ($cm.d^{-1}$)
d	zero plane displacement, dependent on crop height (m)
DAY	day of year
DaE	days after emergence
DDM	defatted dry matter
DEC	declination of the sun (°)
DeltaRD	change in rooting depth (cm)
DeltaZT	change in phreatic level (cm)
Diff	diffuse radiation ($J.m^{-2}.d^{-1}$)
Dir	direct radiation ($J.m^{-2}.d^{-1}$)
DL	day length ($h.d^{-1}$)
DRY	field with no irrigation
DS	surface storage of water (cm)
Dt	length of time interval (d)
DWI(org)	increment in dry organ mass ($kg_{dm}.ha^{-1}$)
DOY	day of year
E	rate of evaporation ($kg.m^{-2}.s^{-1}$)
EAct	actual vapour pressure (mbar)
EC(org)	efficiency of assimilate conversion in plant part 'org' ($kg_{dm}.kg^{-1}_{sugar}$)
Efa	irrigation field application efficiency (on loamy soils around 0.7)
EFF	light use efficiency at low light intensity ($kg.ha^{-1}.h^{-1}/J.m^{-2}.s^{-1}$)
EM	maximum rate of evaporation ($cm.d^{-1}$)
E0	potential rate of evaporation from a wet surface ($cm.d^{-1}$)
Es	potential rate of evaporation from a soil surface ($cm.d^{-1}$)
ETc	potential rate of evapotranspiration by a specific crop ($cm.d^{-1}$)
ET0	potential rate of evapotranspiration by a reference crop ($cm.d^{-1}$)
EXTRA	extraterrestrial radiation ($J.m^{-2}.d^{-1}$)
e_z	actual vapour pressure at z (mbar)
e^*	saturated vapour pressure at Tz °C (mbar)
Pgass	gross rate of assimilate production by a field crop ($kg_{sugar}.ha^{-1}.d^{-1}$)
Fgc	gross rate of CO2-reduction by closed reference crop ($kg_{CO2}.ha^{-1}.d^{-1}$)
FIXZT$	water table depth varies (V) or is fixed (F) over the season
FR	fertilizer requirement ($kg.ha^{-1}$)
FracDiff	fraction of diffuse radiation (-)
fr(org)	mass fraction of assimilates allocated to plant part 'org' (-)
G	heat flux into the soil ($J.m^{-2}.s^{-1}$)
GAA(org)	gross availability of assimilates to plant part 'org' ($kg_{sugar}.ha^{-1}.d^{-1}$)
GAM	texture-specific constant (cm^{-2})
Gamma	psychrometric constant at T24h ($mbar.K^{-1}$)
GROSSUP	gross rate of water supply to the upper boundary of the rooting zone ($cm.d^{-1}$)
h	pressure head (cm)
HALF	field with supplemental irrigation
HEAT	sensible heat flux ($W.m^{-2}$)
HI	harvest index (-)

i	infiltration rate (t)
IE	effective rate of irrigation application ($cm.d^{-1}$)
IM	actual infiltration rate ($cm.d^{-1}$)
INTER	net intercepted radiation ($J.m^{-2}.d^{-1}$)
K	hydraulic conductivity ($cm.d^{-1}$)
K0	saturated hydraulic conductivity ($cm.d^{-1}$)
KAPA	fitting parameter (-)
Kc	crop coefficient (-)
Ke	extinction coefficient for visible light (-)
KPSI	hydraulic conductivity of soil with matric suction PSI ($cm.d^{-1}$)
Ktr	hydraulic permeability of transmission zone ($cm.d^{-1}$)
L	heat of vaporization of water ($J.kg^{-1}$)
LAI	leaf area index ($m^2.m^{-2}$)
LAMBDA	reciprocal value of the air entry suction (cm^{-1})
LAT	latitude of the site (°)
LatHeat	latent heat of vaporization of water at T24h °C ($MJ.kg^{-1}$)
LivS(Leaf)	dry mass of all living leaves ($kg.ha^{-1}$)
LON	longitude of the site (°)
LQ	land quality
LU	land-unit
LUR	land-use requirement
LUS	land-use system
LUT	land utilization type
LWLOSS	long wave radiation loss ($J.m^{-2}.d^{-1}$)
m	empirical parameter (-)
M_a	molar mass of air
MODE$	mode and timing of fertilizer application
MRR(org)	rate of maintenance respiration of plant part 'org' ($kg_{sugar}.ha^{-1}.d^{-1}$)
MUR	maximum rate of water uptake by roots ($cm.d^{-1}$)
M_w	molar mass of water vapour
n	empirical constant (-)
N1	Currently Not Suitable (land suitability class)
N2	Permanently Not Suitable (land suitability class)
NetEnergy	net radiation available for evapotranspiration ($J.m^{-2}.d^{-1}$)
NetRadiat	net shortwave radiation ($J.m^{-2}.d^{-1}$)
NETSUP	net rate of water supply to the underlying root zone ($cm.d^{-1}$)
NSO	nitrogen concentration of storage organ (-)
NStraw	nitrogen concentration of straw (-)
NUR	nutrient uptake requirement ($kg.ha^{-1}$)
NUTCONT	nutrient concentrations of fertilizer (-)
OP	Observation Point
Pa	air pressure (mbar)
PAR	photosynthetically active radiation ($J.m^{-2}.s^{-1}$)
PREC	precipitation ($cm.d^{-1}$)
PI	constant (PI = 3.14159)
PS1	the biophysical production potential
PS2	the water-limited production potential
PS3	the nutrients requirement for target production
PSI	matric suction of rooted soil (cm)
PSIint	matric suction of rooted soil at the time of emergence (cm)
PSIleaf	critical leaf water head (cm)
PSImax	texture-specific suction boundary (cm)
PSO	phosphorous concentration of storage organ (-)
PStraw	phosphorous concentration of straw (-)
R_a	aerodynamic resistance ($s.m^{-1}$)
RaCrop	crop aerodynamic resistance ($s.m^{-1}$)
RAD	conversion factor (degree to radian; RAD = PI/180)
Rad	global radiation ($J.m^{-2}.d^{-1}$)
RadCan	available global net shortwave radiation ($W.m^{-2}$)
Radiat	incoming shortwave radiation at canopy level ($J.m^{-2}.d^{-1}$)
RaGrass	grass aerodynamic resistance ($s.m^{-1}$)
RaSoil	soil aerodynamic resistance ($s.m^{-1}$)
RaWater	water aerodynamic resistance ($s.m^{-1}$)
R_c	crop resistance ($s.m^{-1}$)
RD	equivalent rooting depth (cm)
RDint	equivalent rooting depth at the time of emergence (cm)
RDm	maximum depth of rooting system (cm)
RDN	fraction of SC at latitude 'LAT' and day 'DAY'
RDS	relative development stage (-)
RDSroot	relative development stage at which root growth ceases (-)
RF	fertilizer element recovery fraction ($kg.kg^{-1}$)
RHA	relative humidity of atmospheric air (-)
R_s	stomatal resistance ($s.m^{-1}$)
RLong	net longwave radiation ($J.m^{-2}.d^{-1}$)
R_N	net radiation ($J.m^{-2}.s^{-1}$)

RootLeaf	Root/Leaf-ratio
Rplant	resistance over the distance of moisture flow through the plant (d)
Rroot	resistance over the distance of flow to the root system (d)
RSM	rate of change of volume fraction moisture in rooting zone (d^{-1})
r(org)	organ-specific relative maintenance rate ($kg.kg^{-1}.d^{-1}$)
s	slope of the vapour pressure curve at T_z ($mbar.K^{-1}$)
S0	reference sorptivity ($cm.d^{-0.5}$)
S1	*'Highly Suitable'*
S2	'Moderately Suitable'
S3	'Marginally Suitable'
SC	solar constant (SC = 1353 $J.m^{-2}.s^{-1}$)
Se	relative saturation (-)
SEED	rate of seed use ($kg.ha^{-1}$)
SLA	specific leaf area ($m^2.kg^{-1}$)
SLAmax	maximum specific leaf area ($m^2.kg^{-1}$)
SLAmin	minimum specific leaf area ($m^2.kg^{-1}$)
SM0	total pore fraction ($cm^3.cm^{-3}$)
SMPSI	volume fraction of moisture in soil with suction PSI ($cm^3.cm^{-3}$)
SMR	residual moisture content ($cm^3.cm^{-3}$)
soLf	Storage organ/Leaf-ratio
SPSI	actual sorptivity ($cm.d^{-0.5}$)
SR	rate of surface runoff ($cm.d^{-1}$)
SS	actual surface storage (cm)
SSC	surface storage capacity (cm)
SSIN	sine of latitude
SSint	actual surface storage at the time of emergence (cm)
StLf	Stem/Leaf-ratio
SunH	daily sunshine hours ($h.d^{-1}$)
S(org)	dry mass of plant part 'org' ($kg_{dm}.ha^{-1}$)
T0	threshold temperature for crop development (°C)
T24h	equivalent 24-hours air temperature (°C)
TAir	hourly air temperature (°C)
Tavg	average daily air temperature (°C)
TCM	maximum turbulence coefficient
Tday	day time air temperature (°C)
TDew	hourly dew temperature (°C)
TDiff	difference between canopy temperature and air temperature (°C)
TL	leaf temperature (°C)
TLEAF	heat requirement for full leaf development (°C.d)
TLOW	minimum air temperature for leaf development (°C)
Tmax	maximum daily air temperature (°C)
Tmin	minimum daily air temperature (°C)
Tnight	night time air temperature (°C)
TR	actual rate of transpiration ($cm.d^{-1}$)
TRANS	atmospheric transmissivity (-)
Tref	reference temperature (°C)
TRLOSS	radiation lost for vaporizing water in transpiration ($J.m^{-2}.d^{-1}$)
TRM	maximum rate of transpiration ($cm.d^{-1}$)
TSoil	hourly soil temperature (°C)
Tsset	air temperature at sunset (°C)
TSUM	heat requirement for full plant development (°C.d)
T_z	temperature at z (K)
U	wind speed ($m.s^{-1}$)
U_z	wind speed at Z_a ($m.s^{-1}$)
UPFLUX	net rate of water flow through upper boundary of rooting zone ($cm.d^{-1}$)
VAPFLUX	maximum vapour flux through a mulch layer ($cm.d^{-1}$)
VPD	vapour pressure deficit (mbar)
w	gravimetric water content ($g.cm^{-3}$)
W	leaf width (m)
WATSUPPLY	rate of upward water flow to the lower boundary of the mulch layer ($cm.d^{-1}$)
WET	field with full irrigation
Wind	wind speed ($m.s^{-1}$)
z	height of measurement (m)
Z_a	height of anemometer (m)
Z_o	"roughness height", dependent on crop height (m)
Z_t	height of temperature and humidity measurements (m)
ZT	depth of phreatic level (cm)
ZTint	depth of phreatic level at time of emergence (cm)
φ	dry bulk density ($g.cm^{-3}$)
γ	psychrometric constant ($mbar.K^{-1}$)
θ	volumetric water content (-)
φ_a	air density ($kg.m^{-3}$)
φ_s	specific density of the solid phase ($g.cm^{-3}$)

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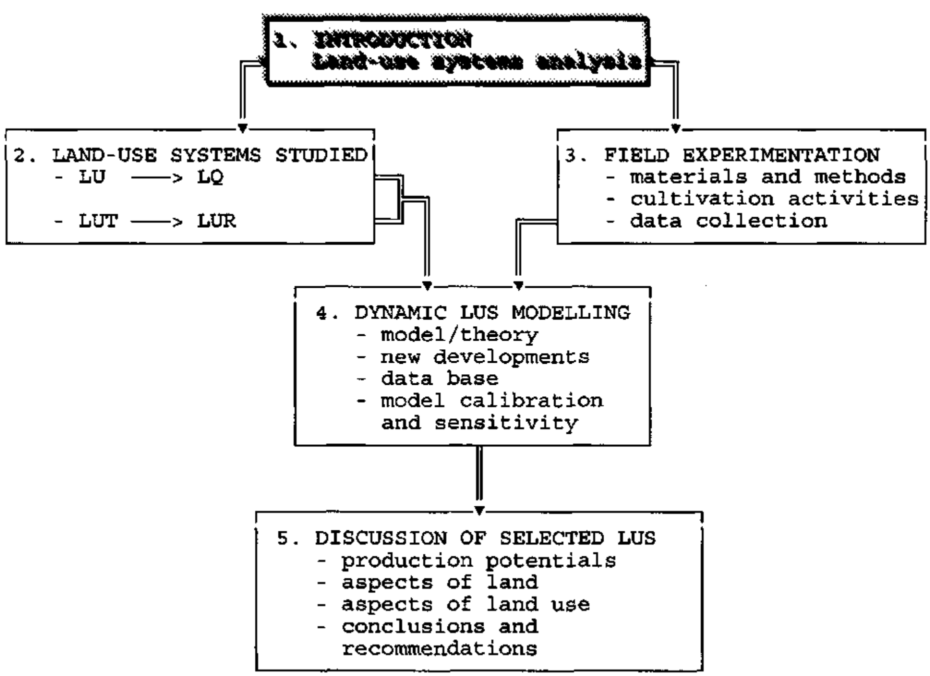
1. INTRODUCTION



Quantified land evaluation

Quantified analysis of land-use systems describes the functioning of a defined land utilization type on a defined land unit over a defined period of time. The land unit is described by its weather and its soil/terrain specifications and is considered internally uniform. The land utilization type is described by its 'key attributes of land use', e.g. by the crop selection and the non-physical aspects of land-use that are relevant to the functioning of the land utilization type (Driessen and Konijn, 1992).

The main purpose of land evaluation is to compare the requirements of the land use with the qualities of the land (Dent and Young, 1981). Land use requirements represent the demands by the crop for unhindered production. These requirements must be met by the land unit that is described by its land characteristics and its land qualities. Land characteristics are single attributes of land that can be measured or estimated. Land qualities are composed of those land characteristics that cover a basic requirement of land-use and influence the land suitability. Land qualities are complex attributes of land that represent the supply side (Driessen and Konijn, 1992).

Land suitability refers to a specific land use. Two suitability Orders ('Suitable" and 'Not Suitable') are subdivided in a number of "suitability classes': 'Highly Suitable' (S1), 'Moderately Suitable' (S2) and 'Marginally Suitable' (S3), and Currently (N1) and Permanently (N2) Not Suitable. The degree of suitability depends on the degree of limitations to sustained application of a given use. Subclasses reflect kinds of limitation (FAO, 1976). These limitations are inadequate land characteristics and land qualities which can be analyzed and the consequences for crop production quantified. Suitability classes can then be defined as a function of production levels: land suitability is a direct outcome of quantified land evaluation.

The biophysical production potential of a land-use system is assessed through quantified land evaluation which allows, in contrast to qualitative methods, a quantitative expression of land qualities, including temporal variability, a more comprehensive evaluation of potential situations, and entails no arbitrary weighing of land characteristics/land qualities (van Lanen, 1991).

Inputs use

Almost all lands can be used for all purposes if sufficient inputs are supplied (Dent and Young, 1981). The use of inputs use can be such that it dominates the conditions in which crops are grown (as it is the case in greenhouse cultivation). Or they can be so low that exhaustion of natural soil fertility forces the farmer to abandon his fields.

The costs of external inputs can be expressed in terms of capital, energy or environment costs, in line with different optimization goals. A comparative evaluation of the technical potential and the economic feasibility of crop production will narrow the range of inputs use at different levels of farm management.

Any land evaluation may quickly lose its relevance. Land qualities may vary in space and time, and new crop varieties or management methods may change the system under evaluation. The consequences of change thus become the fundamental purpose of land evaluation (Dent and Young, 1981).

Changing requirements may call for a change in inputs use, which might not be readily met by the land unit. One solution could be 'land improvement'. Land improvement measures are usually taken at two levels: major and minor. Minor land improvement involves merely land management measures undertaken by the farmer to overcome temporary limitations. The most common are soil tillage and fertilization. Major land improvement involves fundamental changes of the land unit by elimination of a permanent limitation, e.g. by land levelling, that is usually beyond the reach of the farmer. Another solution could be to adapt land use. The choice between land improvement or change of land use is particular acute when agricultural policies are directed towards the development of new settlements.

Land-use systems analysis

Describing crop growth and the associated uptake of water and nutrients by the crop is a complex subject. Simulation models may ask for hundreds of state and rate variables and input data, in line with the lengths of time intervals observed in the simulation and the size of the basic spatial unit. Both spatial and temporal (data) resolutions vary with the aggregation level and purpose of the study (Plentinger and Penning de Vries (Eds.), 1995).

A model is a simplification of reality as it can handle only the most pertinent relationships for the explanation of the system under study. The biggest drawback of simulation would be its use as a blackbox methodology (Varcoe, 1990). Simulation of crop growth should boost the efficiency of the investigative process of field or experimental work provided that it is tailored to the needs of land evaluation.

In the present study, production potentials are calculated at three hierarchical levels of abstraction as a function of environmental factors. At each level, the combination of factors typify a 'production situation'. One distinguishes the biophysical production potential (PS1), the water-limited production potential (PS2) and the nutrient(s) requirement for target production (PS3) (Driessen and Konijn, 1992).

The availability of data for dynamic simulation is often insufficient. One has therefore to work with minimal input data. Daily data values are used and represent the integration over one day.

The higher the level of abstraction, the less data are required but at the cost of lower representativity. One of the advantages of simulation is that it is perhaps the easiest method for extrapolation of experimental results to sites where climate and soil conditions are different (Varcoe, 1990). Unfortunately, this is conducive to the practice of accepting simulated results without validation. To overcome this problem, procedures must be developed for checking the accuracy and reliability of simulation output.

The results of land-use systems analysis remain valid only as long as the variable values which characterize the soil, the climate, the crop and the management do not change.

Generated crop yields for defined production situations, and the associated inputs, can be used to support successive studies at a higher level of aggregation, e.g. land use planning.

A sufficient number of point analysis, with their variabilities over a number of years, may be processed by a geographic information system to yield regional suitability maps of a specific kind of land use. Such maps provide a basis for a rational land use planning, which is founded on the principle that land should be used for what it is best suited for and protected against changes in quality that are difficult to reverse (McRae and Burnham, 1981).

Differences in farmers' skills are not contemplated in this study; it is assumed that they are introduced when integrating biophysical land-use systems analysis with the socio-economic aspects of land use, in a two-stage approach.

Yield analyses are only a first step in the evaluation process. Weather data constitute forcing variables (radiation, temperature and precipitation) for crop production. Even if weather conditions are relatively uniform over, say, tens of hectares, a given crop might not produce the same yield at all places in this area. Crop yield is the result of many interacting aspects of land and land-use. The 'yield gap' between the calculated production potential and actual production can only be narrowed through improved (crop) management. Simulation helps to combine desk research with on-field experimentation and to let farmers participate in active research.

The problem studied

Sunflower production in Spain reached 2 million tons of dry seeds in the 1993/94 campaign. It makes Spain the world's seventh largest producer and the second in the European Community. The area under sunflower increased sharply over the last 30 years, from 10 thousand hectares to 1 million hectares (in Andalusia 420 thousand hectares) (MAPA, 1992). It is the third field crop in acreage, after barley and wheat (Ordoñez and Company, 1990). World oil production from sunflower was 18 million tons in 1985. Only soya bean (100 millions) and cotton (34 millions) contributed more to the world production of vegetable oil (FAO, 1992).

The expansion of the sunflower areal was helped by its easy mechanization. Compared with other crops, sunflower requires few treatments, simple technology and little labour; it is a valuable substitute for wheat in less favourable areas, especially as a dry crop. It benefits from the market is high demand for vegetable oil and from the availability of high yielding varieties (Narciso et al., 1992; Ordoñez and Company, 1990). In Spain and other european countries, communitary policies played a role as well, by guaranteeing base prices.

In commercial crop production, the gap between demand and supply of production means is bridged through inputs. This creates the challenge to achieve one's aims with minimum use of external inputs. The latter may upset the balance between production goals and environmental conditions. Using the land to its best potential is the first step towards sustainability.

The present work tries to build and test a methodology for quantified analysis of specific land-use systems with sunflower. The four major players, i.e. the crop, the soil, the climate and the management, have to be described in numerical terms.

The field experimentation was done near Seville, Andalusia, Spain. A limited number of key properties of the land-use system (usually soil physical and chemical parameters such as pH, clay content, carbonates content, etc.) were examined by linear regression analysis for their effect on crop yield.

Outline of the thesis

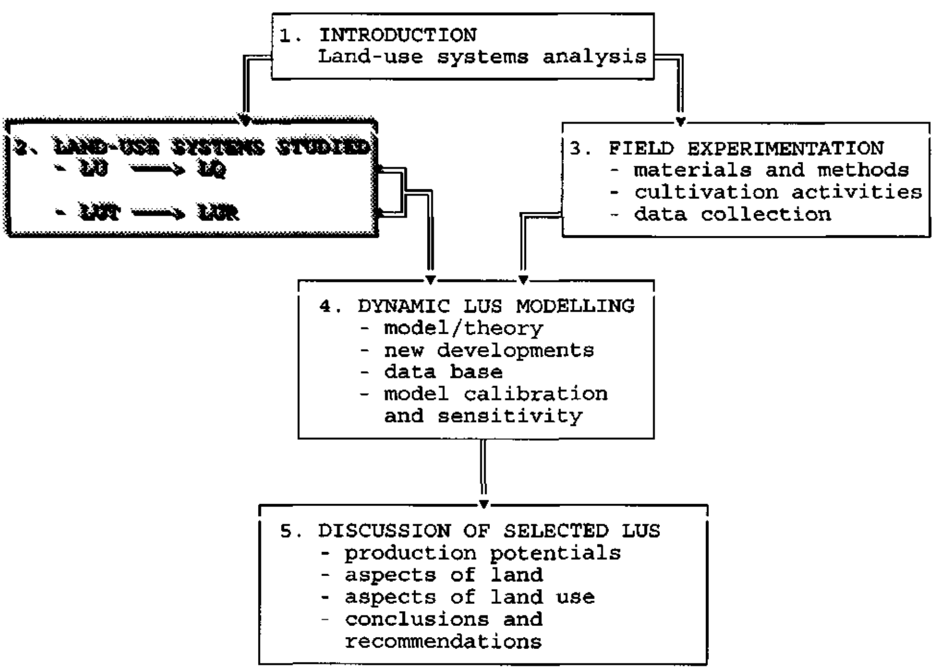
Chapter two of this text characterizes the land-use systems studied and gives a full description of the physical production environment. This concerns the general geographic setting, the land unit and the land utilization types. The geographic setting characterizes 'Andalusia occidental' in terms of climate, geomorphology and soils. The land unit under study is described by its climate and weather data, and by its soil and terrain data. The land utilization types are characterized by their crop (variety) data and by the management applied.

In chapter three, field experimentation is described and the materials and methods for the collection of analytical data presented. Cultivation activities and basic field techniques are described, in particular the crop calendar, tillage, fertilization, irrigation and crop protection. The weather data collected include the daily air temperature, air humidity, precipitation and the number of daily sun hours. The crop data include organ dry matter distribution, leaf area, morphological measurements and data on phenological development. The soil data pertain to soil moisture characteristics, and physical and chemical soil properties.

Dynamic modelling is explained in chapter four. An outline of the model used is given for all production situations. New developments in sunflower research are incorporated in the descriptions of phenology, dry matter partitioning, assimilation, canopy temperature, interception of radiation and evapotranspiration. Finally, model calibration and sensitivity testing is described.

Chapter five deals with production potentials under different production situations, and with specific aspects of land and land use. Conclusions and recommendations are presented.

2. LAND-USE SYSTEMS STUDIED



This chapter describes the physical production environment. A general description of the area is given first; specific land-use systems are described thereafter.

The study area is situated in the Guadalquivir basin of west Andalusia. The geologic-geomorphologic composition of Andalusia comprises three clearly different natural regions: the Hercynian orogeny of the Sierra Morena in the north, the Alpine orogeny of Baetic Cordillera in the south and a tertiary depression, the Guadalquivir Basin, in the middle.

The Sierra Morena constitutes the divide between the basins of the Guadiana and the Guadalquivir rivers. There is a predominance of siliceous lithology, soils are generally acid and shallow mountain soils, used for forestry (cork) and extensive grazing.

The Baetic Cordillera separates the Guadalquivir basin from the Mediterranean Sea. There is a predominance of siliceous and calcareous lithologic materials, soils are generally shallow mountain soils, acid or developed from calcaric rocks, generally used for forestry (wood and cork) and extensive grazing.

The Guadalquivir basin comprises parts of the administrative Provinces of Seville, Cordoba, Huelva, Cadiz and Jaen. It has a triangular shape with a 350 km wide border with the Atlantic ocean and only 10 km wide in the east. Its land surface consist predominantly of alluvial sediments and calcaric colluvial deposits. Agricultural lands are usually calcaric and deep, most of them feature fluvisols, vertisols, luvisols, cambisols and regosols. Intensive production of field crops and fruit trees is concentrated on (irrigated) drylands and makes lavish use of external inputs.

The agroclimate is of the mediterranean type, with cold and humid winters and hot and dry summers. The thermic regime is warm, subtropic in the interior and maritime near the coast. The moisture regime is mediterranean dry (Junta de Andalucía, 1989).

The mean annual temperature is 18 °C, the mean temperature of the coldest month is 10 °C, and of the warmest month 26 °C. The duration of the cold period (mean of minimum temperatures lower than 7 °C) is 3 months, viz December, January and February, and the warm period (mean of maximum temperatures greater than 30 °C) extends from July till October. The first frost occurs on average around 10 October, and the last around 1 March. Annual precipitation amounts to 600 mm (200 in Autumn, 300 in Winter, 100 in Spring and 0 in Summer). A pronounced dry period extends over 4 months. The annual evapotranspiration sum is 900 mm (M.A.P.A. 1989).

2.1. Weather data

A description of long term weather data of Coria del Rio (25 years data set: 1971 to 1995) is presented in chapter 5.

The main weather characteristics are summarized in Fig. 2.1.

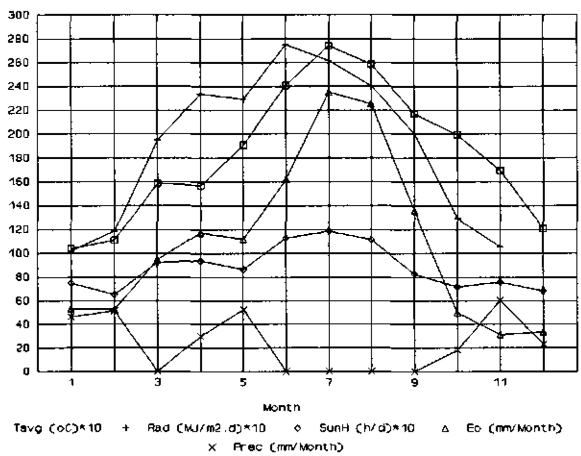


Fig. 2.1. Mean monthly weather data of Coria del Rio, 1994.

2.2. Soil and terrain data

The soils of the experimental farm at Coria del Rio are Calcaric Cambisols, as defined by the FAO-Unesco classification system (FAO-Unesco, 1988). Cambisols are mineral soils of limited genetic age. They show beginning horizon differentiation through changes in colour, structure and/or texture, and are formed from medium to fine-textured materials, mostly in colluvial, alluvial or eolian landscapes (Driessen and Dudal, 1989). They show strong effervescence with 10 % hydrochloric acid. The soil temperature regime is thermic and the moisture regime is xeric.

The landform is an alluvial plain with flat topography. The land element is a terrace in the higher part of the alluvial plain, adjacent to undulating lower hills.

The soil parent material consists of alluvial and colluvial deposits and is derived from limestone. The effective soil depth is 'very deep'; the soil texture is loamy (25 % clay, 31 % silt and 44 % sand), with a bulk density of 1.34 $g.cm^{-3}$ and a porosity of 0.50 $cm^3.cm^{-3}$. The soils may show vertic properties, albeit that cracks are normally too shallow for the soils to classify as vertic. The soils shrink as witnessed by the ratio of bulk densities of wet over dry samples: 0.89.

The soil surface is free of rock outcrops but may contain very few coarse fragments. There is no evidence of erosion. The soil-water regime is characterized by rapid internal drainage; the soils are rarely saturated with water. The soils have a moderate hydraulic conductivity and a very deep ground water table.

Common chemical soil properties are a field pH of 7.5, an ECe value of 0.25 $mS.cm^{-1}$, a carbonate content of 29 %, a C/N ratio of 10 and average NPK values around 0.07 %, 28 $mg.kg^{-1}$ and 293 $mg.kg^{-1}$ respectively. The organic matter content is around 1 %.

The land is planted to sunflower, cotton, wheat and sugarbeet. The soils are modified by tillage, irrigation, application of fertilizers and chemicals, and by mechanized cultivation and harvest practices. A soil profile description according to FAO guidelines (FAO, 1990) is given in Annex A.

Agricultural farms in the area have the following holding size distribution (Mudarra, 1988):

Less than 5 ha	72.5 %
Between 5 and 30 ha	21.7 %
Between 30 and 100 ha	3.7 %
Larger than 100 ha	2.1 %

Some 88 % of the area is privately owned.

2.3. Crop data

Sunflower (*Helianthus annuus* L.) is an annual plant with a single stem and conspicuous, large inflorescence. The height, head size, achene size, and time to mature, vary greatly between varieties. These characteristics vary also with the use of the plant - as a source of edible oil (oilseed sunflower), as food for people (snack) and animals (birdfood and petfood), as a fodder crop or as an ornamental. Wild varieties exist as well (Carter, 1978).

Sunflower thrives in many climates, from (irrigated) arid lands to temperate regions, but is mainly grown as a rainfed crop in temperate climates. Under marginal conditions of rainfall and soil fertility, sunflower often performs better than most other crops (EUROCONSULT, 1989).

The root system has a strong central taproot, with numerous lateral roots in the top 10 to 15 cm of the soil that make up 80 to 90 % of the total root system. In humid soils, the roots extend horizontally; in drier soils they go deeper. The root system is quite sensitive to mechanical obstructions such as a ploughpan or hardpan (CETIOM, 1992).

The stem of cultivated sunflower varieties is typically unbranched. The stem length of commercial sunflower cultivars varies from 50 to 500 cm, with a diameter between 1 and 10 cm (Carter, 1978).

After the first 4 to 5 opposite leaf pairs have formed, a whorled form of alternate phyllotaxy develops. Leaves vary in number, size, shape of the blade, shape of the tip and base, shape of the margin, properties of the surface, hairiness, petiolar characteristics and intensity of colour. These variations seems related to both variety and environmental conditions and cultivation. Stomates are large and more abundant on the lower than on the upper leaf surfaces (Carter, 1978).

The inflorescence is a 'capitulum', or head. It consists of 700 to 3000 flowers in oilseed cultivars, and up to 8000 flowers in non-oilseed cultivars. The head's diameter ranges from 10 to 40 cm; the head may be convex to concave. The disk flowers open centripetally, the outer whorl first. Honey bees are the main pollinating insects (CETIOM, 1992).

The 'achene', or fruit, of sunflower consists of a seed (kernel) and adhering pericarp (hull). All achenes develop a hull even if the seed does not develop. Achenes vary in length from 3 to 20 mm and are 2 to 13 mm wide, and 2.5 to 5 mm thick. The weight of 100 achenes is between 4 and 20 g. The volume density of the seeds is around 390 $kg.m^{-3}$. The oil is highly valued on account of its high content of unsaturated fatty acids (Carter, 1978).

A total biomass production of 10 to 15 ton dry $matter.ha^{-1}$ is possible, with a harvest index of 0.25 to 0.35 (grains/total) (CETIOM, 1992).

Environmental factors and sunflower physiology

Temperature:
The optimal soil temperature at sowing is between 8 and 10 °C. Plants that still have cotyledons can survive short periods of frost. With development, this resistance decreases; frost is critical at the 6 to 7 leaf pairs stage. Sunflower adapts well to both high temperatures (25 to 30 °C) and low temperatures (12 to 17 °C). The optimal temperature is between 21 and 24 °C. The threshold temperature for development is around 6 °C (CETIOM, 1992). The required heat sum depends on the variety and lies between 2100 and 2500 °C.d (at a threshold temperature of 0 °C); the corresponding growth duration is between 120 and 150 days (Ordoñez and Company, 1990).

Light and photoperiod:
Sunflower is a day-neutral plant but short-day varieties exist as well. The daylength responses of sunflower are complex and strongly influenced by temperature. Differences in daylength influence the leaf number per stem and may shift the date of flowering cause by as much as 15 days (Carter, 1978). Sunflower is one of the few plants that do not show signs of saturation at high light intensities (Ordoñez and Company, 1990).

Heliotropism:
The young leaves show heliotropism which gives a 10 to 20 % increase in light interception (Carter, 1978).

Photosynthesis and respiration:
Sunflower's high photosynthetic activity of 40 to 50 mg $CO_2.dm^{-2}.h^{-1}$ is comparable with that of the C4 plants corn and sorghum (Ordoñez and Company, 1990).

The interception of solar radiation by a sunflower crop increases with development and reaches its maximum at flowering, when the leaf area is close to 0.5 m^2 per plant (20 to 30 leaves per plant). The leaves that contribute most to photosynthesis are between leaf numbers 15 and 20. Optimal interception of solar energy is obtained at LAI-values of 2.5 to 3 (CETIOM, 1992).

Latitude:
Latitude is correlated with the temperature and affects the number of days required for flower initiation and also the oil composition (Carter, 1978).

Water:
Sunflower is a lavish user of water if is available, and highly efficient when water is in short supply. The greater the atmospheric demand, the more water sunflower consumes. This is due to its low leaf resistance of 60 to 100 $s.m^{-1}$ (CETIOM, 1992).

Water stress early in the season affects leaf development: the number of leaves is less and leaves are smaller. Water stress after flowering causes mainly an acceleration of leaf senescence (CETIOM, 1992).

At beginning water stress, sunflower closes its stomates on the lower side of the leaves, leaving the stomates on the upper side open to maintain photosynthesis. If water stress goes on, osmotic adjustments allow the plant to maintain the turgor necessary for gas exchange. Wilting of the leaves lowers the angle of solar incidence. Severe stress leads to quick senescence of the lower leaves. Sunflower has a high capacity to recover from water stress (Carter, 1978; Ordoñez and Company, 1990).

An analysis of water use efficiency in different environments suggests that maximum yields will not be obtained if less than 70% of the water requirements are fulfilled (CETIOM, 1992). The total water consumption by sunflower lies between 700 and 1000 mm, depending on climate and length of growing period (Doorenbos and Kassam, 1979).

The water use efficiency (dry matter of the storage organ divided by the water consumed) is between 0.3 and 0.5 $kg.m^{-3}$, for a yield that contains 6 to 10 % moisture. Despite its considerable water use, the crop has the ability to withstand short periods of severe soil water deficit and a total soil moisture potential of up to 15 atmospheres (Doorenbos and Kassam, 1979).

Soil materials:
Sunflower grows well on a wide range of soil materials, from clay to sand, provided drainage is adequate. It has low salinity tolerance (2-4 $dS.m^{-1}$). The pH may vary from 5.8 to more than 8. Sunflower is highly sensitive to aluminum toxicity and to boron deficiency (Ordoñez and Company, 1990).

Cultivation techniques

Crop rotation is needed to reduce the occurrence of pests and diseases and to curb the loss of water and natural soil fertility under sunflower monocropping. A rotation of once in 6 years is widely maintained (Ordoñez and Company, 1990).

Advancing the sowing date slows down development in the first stages, and seeds and seedlings are more exposed to pests and disease. The sowing date must not be within 2 months after the expected last frost. High temperatures are critical at flowering and beginning maturation. Damage by fungi is more likely at cool temperatures and high air humidity (Ordoñez and Company, 1990).

The recommended plant density depends on the availability of water during the growing season. The optimum density is 80000 (irrigated) to 40000 (rainfed) plants per hectare, at a row spacing of 0.9 m. The sowing rate lies between 4 and 10 $kg.ha^{-1}$ (EUROCONSULT, 1989).

Sunflower reacts to planting density by adjusting the number of seeds per head and the average seed weight (Ordoñez and Company, 1990). Good uniformity is required at emergence because sunflower plants are not very forgiving (CETIOM, 1992).

The deep root systems make that 2 to 4 heavy irrigation applications are usually sufficient if the crop is grown on deep, medium-textured soils. A pre-irrigation can be given when required. Applications should be scheduled for the late vegetative and the flowering periods. The most critical period extends from 20 days before to 20 days after flowering. If water is in limited supply, savings can be made during the ripening period. The crop is best grown with surface irrigation, e.g. furrow irrigation that allows infrequent and heavy applications (Doorenbos and Kassam, 1979).

Two weedings of the young sunflower crop are generally sufficient to suppress weeds (EUROCONSULT, 1989).

The most common diseases in sunflower are rust (*Puccinia helianthi*), sclerotinia wilt and head rot (*Sclerotina sclerotiorum*), and downy mildew (*Botrytis cinerea*). The main pests are birds and *Orobanche spp.*, a parasitic plant (EUROCONSULT, 1989).

Varieties

The three sunflower varieties used in this study have the commercial names 'Florasol', 'Islero' and 'Isostar'. The commercial specifications of these varieties are 'medium cycle, medium height, with uniform flowering and maturation, with high yields and oil percentage'. They have also good resistance to lodging, water stress, mildew and *Orobanche*.

The morphological descriptions of these sunflower cultivars use the sunflower descriptors set by the International Board for Plant Genetic Resources (IBPGR, 1985). They are contained in Annex B.

2.4. **Management data**

The field experiments carried out for this study made use of the local management and cultivation practices for rainfed and irrigated production; the objective was to achieve potential production, with the best technical means.

Management variables include the rate of seed use (SEED), the initial rooting depth (RDint), the soil matric suction at emergence (PSIint), the actual surface storage capacity of the land (ASSC), and the depth of the phreatic level at emergence (ZTint). Most of these are affected by water management measures, e.g. by soil and water conservation. The quantity of seeds used is lower when cultivation is rainfed, than when it is irrigated. Sowing depth and sowing date are strongly dependent on the soil's moisture status. The most important instrument to influence the soil water content is irrigation.

Structural hindrances to root development, e.g. a ploughpan or hardpan, condition the maximum rooting depth, and consequently the availability of water for crop growth. Deep ploughing may remove this obstacle.

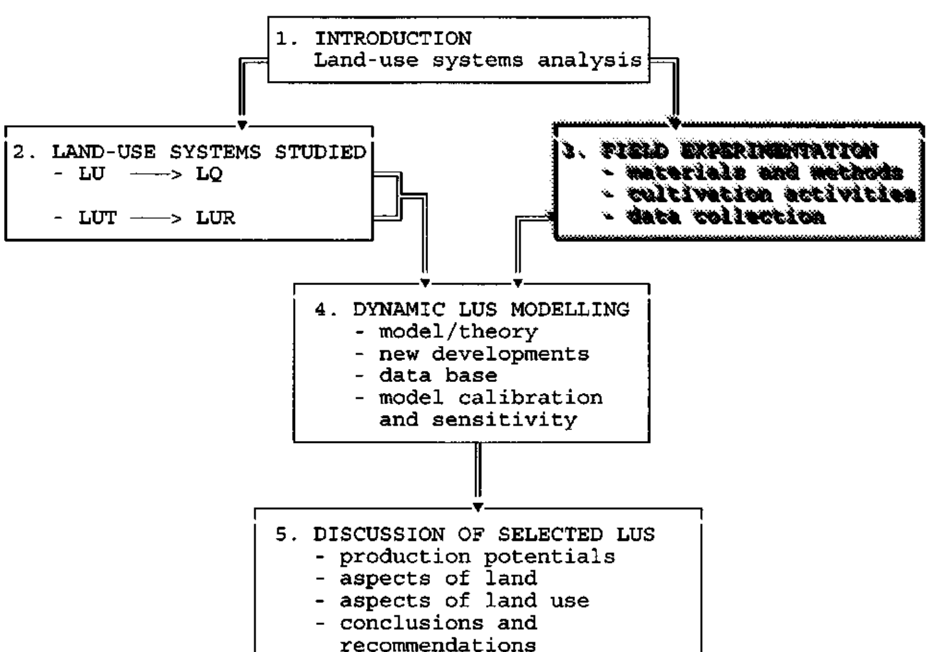
The efficiency of fertilizer(s) application depends inter alia on the fertilizer type and the mode and timing of application. Split fertilizer application increases efficiency, but also costs.

Soil tillage is an important cultivation measure for the land-use systems studied. The purpose(s) of soil tillage and its effects on system parameters are summarized in the following table.

Table 2.1. Soil tillage, purposes and effects.

Purposes	Effects
1. eliminates crop residues from previous season and weeds	1. increases water availability
2. seed bed preparation	2. changes the bulk density
3. facilitates application of fertilizers	3. changes maximum rooting depth
4. opening of furrows for irrigation	4. changes surface storage capacity
	5. changes initial rooting depth
	6. affects the efficiency of fertilizer application

3. FIELD EXPERIMENTATION



Field experimentation was designed to provide information on two production ceilings: the production potential and the water-limited production potential. Fertilization was optimally applied and growth reducing factors were controlled: diseases and pests by preventive chemical control; weeds by preventive chemical control and, during the season, by mechanical control. It may be assumed that no other limiting or reducing factors influenced yield and production, other than radiation and temperature and the availability of water.

Field experimentation was done with three sunflower varieties under three irrigation treatments and with three replications, adding up to 27 plots. The sunflower varieties used were Florasol (from Semillas Cargill S.A., Seville), Islero and Isostar (from Vanderhave Cubian S.A., Marchena-Seville)). The three irrigation treatments were: full irrigation (referred to in the text as WET), supplementary irrigation (HALF) and no irrigation (DRY). The WET treatment represents Production Situation 1, potential production, and the others are PS2 scenarios with different water-limited production potentials.

The plots were 112 m^2 each (20 m long * 5.6 m wide). The width chosen accommodated 8 rows of plants 0.70 m apart. For an estimated plant density of 4 plants per meter this results in 640 plants per plot, equivalent to around 57 000 plants per hectare. The plots were arranged in three groups with different irrigation treatments, and with two blocks per treatment. Soil sampling or measurements were done on blocks or at observation points. In between blocks, there was a 4 meters wide path. The experimental design is shown hereafter.

Table 3.1. Experimental design

a. Blocks and treatments

3	2	1
6		4
DRY (3,6)	HALF (2,5)	WET (1,4)

b. Distribution of varieties

C	A 2	B	A	B	A	B	A	C	A	B	C	A 1	C
C	A	B	C	B	C	B	A	C	A	B	C	B	

where: Varieties are A Florasol; B Islero; C Isostar
Observation points (OP) : 1 and 2

Field experimentation was done in 1993 and 1994 at the experimental farm of the Institute for Natural Resources and Agrobiology of Seville (IRNAS) in Coria del Rio. Sunflower was grown according to the locally used crop calendar.

3.1. Cultivation activities

Cultivation activities are measures taken or operations in the process of sunflower production, notably tillage, fertilization, irrigation and crop protection measures. The crop calender schedules these activities over the growing period.

Crop calendar

The crop calendars for the two years of experimentation are shown in Tables 3.2.a. and 3.2.b.:

Table 3.2.a. Crop calendar 1993.

Date	Day	Operation	Other measures
I/1	-75	Grading (destroy cotton residues)	
I/1		Deep ploughing (35 - 40 cm)	
I/2	-45	Grading (destroy big peds)	
III/2	-30	Cultivator (9 arms)	
5/3	-17		* SS1
9/3	-13	Apply N fertilizer (deep); Grade	
11/3	-11	Cultivator (9 arms+table+roll)	
18/3	-4	P fertilizer (deep)	
20/3	-2	Harrowing	
22/3	0	Sowing (+ insecticide)	* SM
23/3	1	Roll + herbicide	
2/4	11	(*Emergence*)	* SM
5/4	14		* SS2; 1Hst; 1LAI
12/4	21		* SM; Kipp; Tens; PSI;SM
19/4	28	Harrowing	* 2Hst; 2LAI; SM
26/4	35		* SM
3/5	42		* 3Hst;3LAI;SM;RW1
6/5	45	Clearing	
7/5	46		* SS3
10/5	49	Harrowing	* SM
17/5	56		* SM
18/5	57	Harrow	
20/5	59	(*Plants with small capitella*)	
24/5	63		* 4Hst; 4LAI; SM
31/5	70		* SM
1/6	71	N fert.(cover);Irrig. (Wet + Half)	
4/6	74		* Kipp
5/6	75		* Phenol
7/6	77		* SM; SS4; LS1
8/6	78	Irrigation (Wet)	* PSI
13/6	83	(*Plants with flower*)	
14/6	84		* SM
15/6	85	Irrigation (Wet + Half)	* 5Hst; 5LAI; PSI
20/6	90		* LS2
21/6	91		* SM
22/6	92	Irrigation (Wet)	
28/6	98		* SM
29/6	99		* LS3
30/6	100	Irrigation (Wet)	
1/7	101		* PSI
5/7	105		* SM
6/7	106	Irrigation (Wet + Half)	* 6Hst; 6LAI; SS5; WS2
9/7	109		* PSI; LS4
12/7	112		* SM; Kipp
13/7	113	Irrigation (Wet)	
14/7	114		* Phenol

15/7	115		* Density
20/7	120		* SM
21/7	121		* 7Hst
22/7	122		* Nets; WS3
26/7	126		* SM; Phot
2/8	132		* SM; LS5; Kipp
3/8	133		* 8Hst Dry; Seed
10/8	140		* 8Hst Half
13/8	143		* SS6
17/8	147		* 8Hst Wet

Table 3.2.b. Crop calendar 1994.

Date	Day	Operation	Other measures
II/10	-143	Grading (5 arms)	
II/11	-112	Cultivator (9 arms)	
22/2	-14	Cultivator (9 arms)	* SS1
25/2	-11	N & P fertilization deep; Grade	
8/3	0	Sowing (+ insecticide)	* SM
9/3	1	Herbicide application	
15/3	7		* WS1
18/3	10		* SM
25/3	17	(*Emergence*)	* 1Hst;1LAI;1SLA;SM;Tens
1/4	24		* SM
4/4	27		* SS2
5/4	28		* Kipp
8/4	31		* SM
12/4	35		* 2Hst; 2LAI; 2SLA
15/4	38		* SM
22/4	45		* SM
25/4	48	Harrowing	* Kipp
26/4	49	Clearing	
29/4	52		* SM
2/5	55		* SS3; PSI
3/5	56		* 3Hst; 3LAI; 3SLA
4/5	57	Harrowing	
6/5	59		* SM
9/5	62	N fert.(cover); Irrig.(Wet + Half)	
14/5	67		* SM
20/5	73		* 4Hst; 4LAI; SM
21/5	74		* PSI
23/5	76		* Density
27/5	80		* SM
30/5	83	(*Flowered field*)	
1/6	85		* 4SLA
2/6	86	Irrigation (Wet)	
3/6	87	(*Plants wilting* (Dry))	* SM; SS4; Kipp
6/6	90		* Phenol
7/6	91	Irrigation (Wet + Half)	* PSI
10/6	94		* SM
13/6	97		* 5Hst; 5LAI; 5SLA
14/6	98	Irrigation (Wet)	
16/6	100	Nets (Dry)	
17/6	101		* SM
20/6	104		* Kipp
21/6	105	Irrigation (Wet + Half)	* PSI, WS2
22/6	106	Nets (Half)	
23/6	107	Nets (Wet)	
24/6	108		* SM
28/6	112	Irrigation (Wet)	
30/6	114		* Phenol
2/7	116		* SM
4/7	118		* 6Hst; 6LAI; 6SLA
5/7	119	Irrigation (Wet)	* LS
6/7	120		* SS5

7/7	121	* Phenol
8/7	122	* SM
15/7	129	* SM
18/7	132	* 7Hst Dry; Seed
21/7	136	* LS
22/7	137	* SM
23/7	138	* 7Hst Half; Seed
29/7	144	* SM
30/7	145	* 7Hst Half; Seed
3/8	149	* SS6

Legend:

SM	: Soil sampling for water content.
SS1 and SS6	: Soil samples (0 - 150 cm) 6 depths * 6 blocks.
SS2 to SS5	: Soil samples (0 - 100 cm) 4 depths * 2 OP.
WS	: Irrigation water sample.
RW	: Rain water sample.
nHst	: Harvest number and partitioning measurement.
nLAI	: LAI measurement.
nSLA	: Measurement of specific leaf area.
Kipp	: Radiation measurement.
Tens	: Beginning of tensiometer measurement.
PSI	: PSI measurements.
Phenol	: Description of phenology.
LS	: Leaf (LS1 to LS4) or plant samples (LS5).
Density	: Measurement of plant density.
Nets	: Fix nets to protect against birds.
Seed	: Seed samples for oil quality.

The measurements are further explained in section 3.2.

Soil tillage

Soil tillage was done for several purposes, viz. to:
- destroy previous season's crop residues
- cultivate the soil (deep ploughing and harrowing)
- prepare the seed bed
- facilitate fertilizers application
- control weeds
- open furrows for irrigation

A farm tractor with implements (deep plough, grade, cultivator, table, roll) was used for tillage and draft animals with a light plough were used for mechanical weed control and for opening up irrigation furrows.

Irrigation

Surface irrigation was applied only. The farm's main distribution pipe was fitted with a plastic "head pipe" with one outlet per furrow and positioned along the outer border of blocks 4 and 5. The furrows were made perpendicular through blocks 4 and 1, and 5 and 2. These furrows were 45 m long.

Timing of water supply and applications are summarized in Tables 3.3.a. and 3.3.b. where

RAIN refers to precipitation and WATER represents the total water input by precipitation and irrigation. Individual applications are listed under Day and cumulative values under Accu.

Table 3.3.a. Water inputs 1993

				RAIN		WATER					
						Wet		Half		Dry	
DOY	Date	DaE	Observations	Day	Accu	Day	Accu	Day	Accu	Day	Accu
82	22/03	-11	Sowing	till=	96						
83	23/03	-10									
84	24/03	-9		10	10	10	10	10	10	10	10
93	02/04	0	Emergence								
94	03/04	1		10	20	10	20	10	20	10	20
96	05/04	3	* 1Hst								
110	19/04	17	* 2Hst								
114	23/04	21		9	29		29		29		29
115	24/04	22		2	31		31		31		31
116	25/04	23		7	38		38		38		38
117	26/04	24		9	47		47		47		47
118	27/04	25		7	54		54		54		54
120	29/04	27		9	63		63		63		63
123	02/05	30		14	77		77		77		77
124	03/05	31	* 3Hst	4	81		81		81		81
127	06/05	34	Clearing								
131	10/05	38		24	105		105		105		105
132	11/05	39		5	110		110		110		110
133	12/05	40		2	112		112		112		112
141	20/05	48	Small capitella								
145	24/05	52	* 4Hst	2	114		114		114		114
146	25/05	53		7	121		121		121		121
153	01/06	60	N cover			47	168	47	168		
160	08/06	67				29	197				
165	13/06	72	Flower								
167	15/06	74	* 5Hst			33	230	33	201		
172	20/06	79		4	125		234		205		125
173	21/06	80									
174	22/06	81				34	268				
180	28/06	87	Dry dead								
182	30/06	89				32	300				
188	06/07	95	* 6Hst			27	327	31	236		
195	13/07	102				27	354				
203	21/07	110	* 7Hst								
216	03/08	123	* 8Hst (Dry)								
223	10/08	130	* 8Hst (Half)								
230	17/08	137	* 8Hst (Wet)								
	Total:		Pre-irrigation :							20	
			Rain :	105							
			Pre + Rain :		125						
			Irrigation (Wet) :			229					
			Irrigation (Half) :					111			
			Total (Wet) :				354				
			Total (Half) :						236		
			Total (Dry) :								125

Table 3.3.b. Water inputs 1994

				RAIN		WATER					
						Wet		Half		Dry	
DOY	Date	DaE	Observations	Day	Accu	Day	Accu	Day	Accu	Day	Accu
68	08/03	-17	Sowing	till=	98						
75	15/03	-10		18	18	18	18	18	18	18	18
85	25/03	0	* 1Hst								
87	27/03	2		16	34	16	34	16	34	16	34
103	12/04	18	* 2Hst	24	58	24	58	24	58	24	58
105	14/04	20		12	70		70		70		70
106	15/04	21		9	79		79		79		79
109	18/04	24		2	81		81		81		81
110	19/04	25		1	82		82		82		82
113	22/04	28		3	85		85		85		85
114	23/04	29		5	90		90		90		90
116	25/04	31	Clearing								
124	03/05	39	* 3Hst								
130	09/05	45	N cover		90	40	130	44	134		90
133	12/05	48		13	103		143		147		103
134	13/05	49		8	111		151		155		111
135	14/05	50		1	112		152		156		112
136	15/05	51		12	124		164		168		124
138	17/05	53		5	129		169		173		129
141	20/05	56	* 4Hst								
144	23/05	59		14	143		183		187		143
151	30/05	66	Flowered								
154	02/06	69			143	29	212		187		143
155	03/06	70	Dry wilt								
159	07/06	74			143	21	233	31	218		143
165	13/06	80	* 5Hst								
166	14/06	81			143	30	263		218		143
173	21/06	88			143	26	289	40	258		143
180	28/06	95			143	29	318		258		143
186	04/07	101	* 6Hst								
187	05/07	102			143	26	344		258		143
200	18/07	115	* 7Hst (Dry)								
205	23/07	120	* 7Hst (Half)								
212	30/07	127	* 7Hst (Wet)								
	Total:		Pre-irrigation :							58	
			Rain :	85							
			Pre + Rain :		143						
			Irrigation (Wet) :			201					
			Irrigation (Half) :					115			
			Total (Wet) :				344				
			Total (Half) :						258		
			Total (Dry) :								143

Fertilization

Nitrogen and phosphorus fertilizers were applied twice, once before sowing (deep N and P application), and as an N top dressing after appearance of the capitella.

Rates of fertilizer application:

N fertilizer: deep : Urea 46% 150 kg.ha^{-1}.
top dressing : Urea 46% 100 kg.ha^{-1}.
P fertilizer: Superphosphate calcic 45 % P_2O_5 100 kg.ha^{-1}.

This brings the total input of nutrients at 15 kg nitrogen and 20 kg phosphorus per hectare.

Crop protection

To free the experiments of growth reducing factors, prevention measures and curative measures were taken as required. The measures included chemical weeds and pests control at sowing time and mechanical weeds control along the growing period.

Rates of applied chemicals at sowing:

```
Mezurol  : Bird repellent 200 g.ha-1
Lindano  : Soil insecticide 2 %, 25 kg.ha-1
Terburex : Herbicide, 2 l.ha-1
```

3.2. Data collection and data screening

Methods (equipment, partial harvests, dates)

Field measurements and laboratory analyses provided additional data to describe the land-use systems studied. Tables 3.2.a. and 3.2.b. contain information on the frequency of samplings and measurements.

The legend of Tables 3.2.a. and 3.2.b. shows which measurements were done. The following explains how they were performed:

SM : Soil sampling for water content.
Soil samples were taken from different soil depths (15, 30 and 45 cm) at two observation points in the experimental field. These samples were weighted fresh, dried in an oven at 105 °C for 24 hours and weighted once more. The moisture lost was used to calculate the gravimetric water content. Knowing the dry bulk density of the soil, the volumetric water content could be calculated.

```
SS1 and SS6 : Soil samples (0 - 150 cm) 6 depths * 6 blocks.
SS2 to SS5  : Soil samples (0 - 100 cm) 4 depths * 2 OP.
WS          : Irrigation water sample.
RW          : Rain water sample.
```

nHst : Harvest number and partitioning measurement.
Dry matter production and distribution were monitored in successive partial harvests. This means that part of the field was harvested, partitioned into plant organs, measured and weighed fresh, dried and weighed again. The drying was done in an oven at 90 °C for 24 hours. Plant material that was too large to be put in the oven, was dried in a glasshouse first. In this way data was gathered on fresh and dry matter weights of: roots, stems, leaves and storage organs, the latter broken down in seeds and head. Root and stem lengths, stem base, top diameter and head diameter were recorded as well.

nLAI : LAI measurement.
Leaf area was measured for each pair of leaves in partial destructive harvests using a portable

area meter (Model LI-3000, LI-COR) . Leaf status was recorded as "green", "dry" or "absent". Thus, total leaf area, green leaf area, distribution of leaf area within the canopy and plant leaf pairs were recorded.

nSLA : Measurement of specific leaf area.
Specific leaf area is the leaf area in m^2 per kg dry leaf mass. The leaf mass was split into limb and petiole; calculated SLA values refer to leaf limb and not to the whole leaf.

Kipp : Radiation measurement.
Radiation was measured using a Kipp solarimeter. The direction and surfaces used permit to compute the albedo for specific surfaces as well as light extinction in the crop canopy. The global incoming radiation above the canopy, in the canopy, and over water, bare soil and grass were established.

Tens : Beginning of tensiometer measurement.
Tensiometers were installed at the two observation points at depths of 10, 30, 45 and 60 cm. Readings were done daily. Near the end of the growing season, when the soil had become quite dry, the tensiometers failed.

PSI : PSI measurements.
These PSI measurements served to establish the critical leaf water head. To compute it, two approaches were tested. One method was to grow plants in closed buckets (transplanted from the field) and let them grow until they start to wilt. At this point soil samples were taken for measuring the soil moisture content. The method seemed to work well if the plants are small. Alternatively, soil samples from the root ball of plants that started to wilt in the field (in dry blocks) were taken for measurements of soil moisture content. This method was more appropriate for older plants.

Phenol : Description of phenology.
The description of phenology serves to characterize the development of the crop throughout the growing period. Phenology was monitored regularly by means of field observations of philothaxy, organ status, development and senescence. A morphological description was made for each variety.

LS : Leaf (LS1 to LS4) or plant samples (LS5)
Plant sampling for laboratory analysis.

Density : Measurements of plant density.
The estimated average plant density was around 57000 plants per hectare, but plant density was measured for each plot.

Nets : Fix nets to keep birds out.
Birds are the first harvesters that come to the fields. Nets were used to minimize seed loss.

Seed : Seed samples for oil quality analysis.

Data collection (climate, soil, crop)

Laboratory analyses

Laboratory analyses were done on:

A. Soils
   a. Every month during the growing season: pH, EC, NPK contents.
   b. Before and after the growing season:
      Texture (sand, silt, clay), organic matter content, carbonates content and CEC.
   c. Soil analysis for soil profile description (once).
   d. Water retention curve (once).
   e. Hydraulic conductivity curve (once).

B. Irrigation water and rain water (several times): pH, EC, SAR

C. Plant tissue and seeds
   a. Leaves, stems and roots (several times): tissue analysis of NPK contents.
   b. Seeds (2 times) to establish oil quality.

The data obtained through laboratory analyses are summarized in Annex A.

Weather data

Climate data were collected at the meteorological station of the experimental farm of the Institute for Natural Resources and Agrobiology of Seville (IRNAS) in Coria del Rio. Daily maximum and minimum temperatures, precipitation, relative air humidity, sun hours and evaporation were determined with standard meteorological procedures.

The weather data are listed in Annex C.

Crop data

Crop data were established through field measurements. These were done for three replications; the data on record are the normal average.

The basic measurements are:
- organ fresh weight.
- organ dry mass.
- leaf area.
- plant density.
- plant phenology.
- root length.
- stem length.
- base and top stem diameter.
- head diameter.

Combination of one or more of these basic measurements yields the following data:

- organ fresh weight ($kg.ha^{-1}$).
- organ dry mass ($kg.ha^{-1}$)
- seed content of the storage organ (%).
- organ dry matter partitioning (%): percentage of dry organ mass as a percentage of the total dry mass of the plant.
- organ dry matter ratios (-): ratios of dry organ masses, e.g., leaf to stem ratio, leaf to root ratio, shoot to root ratio.
- moisture content (%) (total or by organ).
- total number of leaf pairs.
- number of green leaf pairs.
- number of dry leaf pairs.
- percentage of green leaf pairs (%).
- leaf area ($cm^2.plant^{-1}$).
- leaf area index (-): cumulative leaf area divided by ground area.
- SLA ($m^2.kg^{-1}$): cumulative leaf area over leaf dry weight.
- leaf to petiole dry matter ratio (-).
- head diameter (cm).
- head area (cm^2).
- head area as percentage of leaf area (%).
- equivalent root depth (cm).
- stem height (cm).
- stem volume (cm^3): calculated from stem height and stem base and top diameters.
- base diameter (cm) at stem divide with the root.
- cumulative leaf area ($cm^2.plant^{-1}$).

Crop data are listed in Annex B.

Soil data

Field measurements and laboratory soil analyses include:

1. Double ring infiltration measurements.
2. Hot-air method for measuring hydraulic conductivity at high soil suction.
3. pF measurements.
4. Bulk density measurements.
5. Soil profile descriptions.
6. Soil texture determinations.
7. Gravimetric determinations of soil water content.
8. Tensiometer readings.
9. Rooting depth and pattern.
10. PSIleaf measurements.
11. 'Multi-step outflow' determinations of hydraulic conductivity at low soil suction.

These data were collected with the following methods:

1. Double ring infiltration method.

Measurements were done at four locations. Soil moisture contents were determined before and after the measurement. A description of the method can be found in Bouwer (1986).

2. Hot-air method

Measurements to determine KPSI-relations at high suction (10^3-10^5 cm) were done on samples from four locations. A description of the method can be found in Arya et al., 1975; a discussion of the method is given by van Grinsven et al., 1985.

3. pF measurements

pF measurements were done at four locations. Each series of measurements comprised pF 0.5, 1.0, 1.2, 1.5, 2.5 and 4.2. From pF 0.5 till pF 1.5 the water content was determined by suction applied to undisturbed prewetted soil in sample rings of 2 cm height and with a volume of 100.5 cm^3. At pF 2.5, the water content was determined in pressure cans, with undisturbed samples of the same size and volume as above. For pF 4.2, the water content was determined on disturbed samples in small rings. All measurements at suction values below pF 2.5 were done on the same samples. The undisturbed samples were weighed twice, once at pF 1.5 and again at pF 2.5. After determining pF 2.5, the sample was dried and weighed again to determine its bulk density and total water content.

4. Bulk density measurements

Bulk density was determined as part of the infiltration measurements and in the course of pF and hot air KPSI measurements. For the infiltration measurements, the water content of the soil before and after the experiment was determined in 5 cm high rings of 100 cm^3. Recall that the pF samples used 2 cm high rings of the same volume. The "hot air samples" came in 10 cm high rings with a volume of 200 cm^3. There were considerable differences between the results of the four sampling methods.

5. Soil profile descriptions

A pit was dug to a depth of 2.25 meter and a soil profile description made according to FAO guidelines (FAO, 1990). The soil was classified according to the FAO classification system (FAO, 1988). Samples were taken from every horizon for determination of pH, EC, organic matter content, texture and presence of carbonates.

6. Soil texture determinations

Soil texture was analyzed in Seville and in Wageningen. Soil samples for nutrient analysis were taken at OP1 and OP2 every month. In March and August, 6 sites were sampled to a depth of 1.5 meter (intervals 0-30, 30-50, 50-70, 70-100, 100-130, 130-150 cm). In all other months the soils were sampled down to 1 meter (with 4 intervals: 0-30, 30-50, 50-70 and 70-100 cm). All samples were analyzed for texture (first month only), pH, carbonate content, organic matter content, C/N ratio and carbon, nitrogen, phosphorus and potassium contents.

7. Gravimetric determination of the soil water content

Soil water contents at 3 depths (0-15 cm, 15-30 cm and 30-45 cm) were determined every week at OP1 and OP2, with 3 repetitions. During the first weeks only the first and second depth were sampled. Samples were taken with an Edelman auger and with the Cobra mechanical auger.

8. Tensiometer readings

Tensiometers were installed at 4 depths (15 cm, 30 cm, 45 cm and 60 cm) at OP1 and OP2. The tensiometers were read every day to measure suction till 1000 hPa. They were checked and filled at least once a week. In May, the non-irrigated plots became too dry and the tensiometers failed. In irrigated plots, they were useful only for a few days after irrigation because of drying of the soil.

9. Rooting depth and pattern

Root length were measured at each harvest and dry root mass determined. The maximum rooting depth was determined by augering with the Cobra at the location of a plant down till a depth of 2 meters. The soil cores were examined for the presence of roots. The rooting pattern under water stress was studied at the border of the irrigated and non-irrigated plots. It showed that roots were not randomly distributed but tended to grow in the direction of the water.

10. PSIleaf measurements

The soil moisture potential at irreversible wilting was determined in two ways. First 9 plants were removed from the field, placed in buckets and irrigated for a few days till they had recovered. No water was given thereafter. The moisture content of the soil was determined at the beginning of wilting. With the aid of the pF-curve, the corresponding PSI was determined.
Alternatively, plants that had just started wilting were spotted in the field. The soil moisture content near the plant was determined and the plant was irrigated. The next day, it was observed if the plant had recovered. These experiments were repeated 5 times.

11. Multi-step outflow determination of hydraulic conductivity

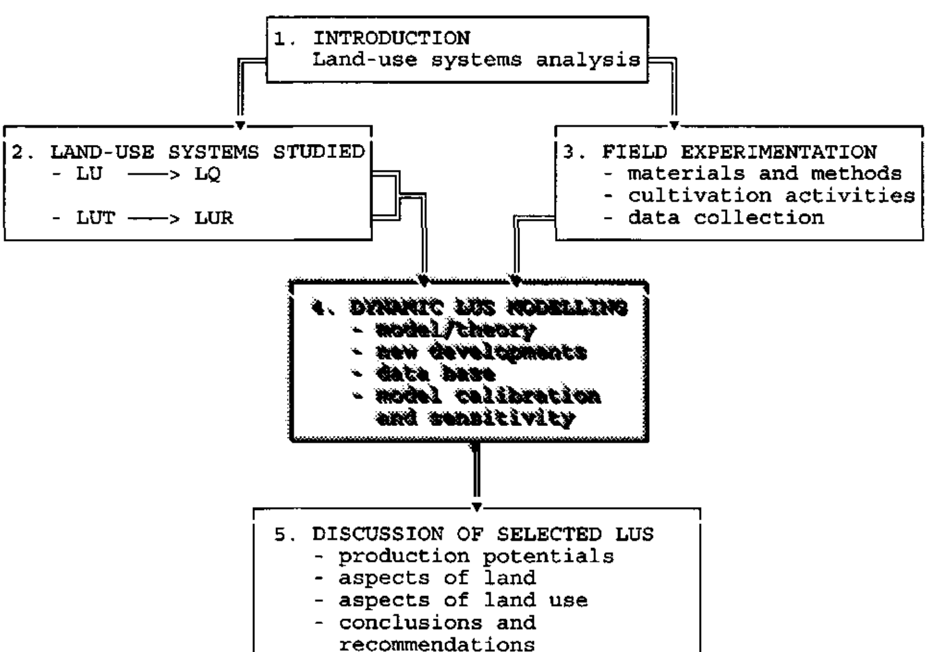
The multi-step outflow method applies various pressures (from low to high) to a relatively wet soil sample that has been placed in a pressure cell. Outflow from the bottom of the sample is collected and plotted against time. The SFIT model was used to optimize the parameters and to generate the KPSI-PSI curve. A description of the method is given by Booltink et al., 1991. Measurements were done on eight samples, four taken near the surface and four at 30 cm depth. The samples were processed in Wageningen.

Soil data are listed in Annex A.

Data screening (internal consistency)

Data were gathered through different procedures, techniques and equipment. Data screening is needed to check (internal) consistency and for patching missing data in a set.
Internal consistency checks trace conflicting data values, e.g. a high radiation level on a completely overcast day, or a total number of sun hours greater than the day length.

4. DYNAMIC LAND-USE SYSTEMS MODELLING



4.1. Outline of the model

The model used for land-use systems analysis is a 'policy support model'. It is a comprehensive, deterministic crop production model, developed for dynamic simulation of land qualities and corresponding land use requirements, in rigidly defined production situations.

A policy support model is typically less detailed than an analytical model. It describes the most important processes, their interactions and their effects on crop growth. It is based on fundamental physical, chemical and biological laws, to warrant that it is transportable. It is adapted to the purpose and scale of particular land evaluation exercises.

The model uses the "state variable approach", i.e. it considers the growth cycle as a concatenation of daily time intervals. Dependent variable values are assumed steady for the duration of an interval and reflect the state of the system during that interval. All variable values are adjusted after completion of the calculations for an interval. The adjusted values typify the state of the system during the next interval.

The length of the time intervals is set to one day, commensurate with the resolution of the available data and the dynamics of the system.

Production potentials can be calculated at several hierarchical levels. At each level, one (additional) set of a land quality and related crop requirements is examined. At the highest level (PS1) crop growth is assumed to depend on the availability of radiation and temperature only. At the second highest level (PS2), the water-limited production potential is calculated considering the availability of water for uptake in addition to temperature and radiation. The nutrient requirement for realizing a target production is calculated at the third level (PS3). To estimate the actual harvest one would have to account also for all reducing factors, e.g. pests, diseases, weeds, pollutants, mismanagement and all harvest and post-harvest losses.

At production situations PS1 and PS2, production and yield are dependent variables, i.e. they are the outcome of calculations. At PS3 production and yield are postulated as a target production whose ceiling is defined by the PS2 level, and the program calculates the nutrients required to realize the target.

The model is described by Driessen and Konijn (1992).

The biophysical production potential

Crop production at the highest hierarchical level refers to a system where only the availability of solar radiation and the photosynthetic energy requirement at the prevailing temperature determine the production potential of the land use system. It is assumed that no other limiting factors or reducing factors influence crop performance. Production and yield depend on the ability of the crop to use the energy at the site for assimilation and growth.

The climatic conditions of the land use system are characterized by the maximum and minimum temperature, the relative air humidity and the number of sun hours in each day.

The latitude of the site and the day in the year permit to calculate extraterrestrial radiation and day length.

Photosynthetically active radiation (PAR) that reaches the canopy, is calculated from extraterrestrial radiation accounting for radiation losses by suboptimal atmospheric transmissivity, which is approximated as a function of the site, the air humidity, the number of sun hours and the day length.

The maximum assimilation rate depends heavily on the photosynthetic pathway of the crop, (whether it is a C3 or a C4 plant) and by crop characteristics such as the light use efficiency at low light intensity (EFF) and the maximum rate of assimilation at actual temperature (AMAX). The actual rate of photosynthesis is co-determined by the canopy structure (shape, surface properties and position of the leaves) that determines how incoming radiation is distributed over the canopy, and by the extinction coefficient for visible light (Ke). The quantity of assimilates produced varies with canopy dimensions characterised by the leaf area index (LAI) that is calculated as a function of the specific leaf area (SLA) and the cumulative living leaf mass.

The processes considered in PS1 calculations are:

a. Production of assimilates as a function of PAR, DL, LAI, AMAX, EFF and Ke.

b. Allocation of the assimilates produced to the various plant organs.

c. Loss of assimilates in respiration to maintain living material.

d. Conversion of the remaining assimilates in structural plant matter.

Before calculation of dry weight increments during the next time interval, all organ dry masses are adjusted by the respective (calculated) dry weight increments. The total dry plant mass is the sum of all plant organ masses. The calculations proceed until full physiological development is reached.

The rates of assimilation and maintenance respiration are affected by the availability of water. By definition, PS1 is free of water stress, and no correction for suboptimal availability of water is required (CFWATER = 1).

The water-limited production potential

The correction factor for suboptimal availability of water is CFWATER, i.e. the ratio of actual and maximum transpiration rates. The structure of the PS1 calculations is fully maintained in calculations at level PS2; only a water balance is added to PS1. The correction factor, CFWATER, is the expression of the sufficiency of water availability.

The rooted surface soil is treated as one compartment; its upper boundary is the soil surface and its lower boundary is at an equivalent rooting depth that changes over the growing season. The sources of water in the water balance are precipitation, irrigation and capillary rise; evaporation, transpiration, surface runoff and deep percolation/drainage, act as sinks.

The soil has a specific moisture retention curve (SMPSI-to-PSI relations), unsaturated hydraulic conductivity curve (KPSI-to-PSI relations) and infiltration parameters.

The rate of change of the volume fraction of moisture in the rooted surface compartment (RSM) depends on the fluxes of water (vapour) through its two boundaries and on water extraction by roots for transpiration.

Water fluxes through the lower boundary of the rooted surface compartment are composed of deep percolation (D) and capillary rise (CR). Both processes follow the general flow equation. The depth of the phreatic level (ZT), may be fixed e.g. in the case of forced drainage, or vary over the season. The change in depth of the phreatic level (DeltaZT) is made dependent on the rise of the ground water by a predominance of deep percolation or by its fall as a result of capillary rise.

The actual rate of transpiration (TR) is found by matching the maximum rate of water uptake by roots (MUR) and the maximum rate of transpiration (TRM). MUR is the result of the difference in water potential between the soil and the plant, and the respective root and plant resistances to the flow. It represents the supply side. TRM, the demand side, is calculated from the potential rate of evapotranspiration corrected for actual soil cover and the effects of air turbulence. If MUR > = TRM then TR = TRM else TR = MUR.

Fluxes through the upper soil (UPFLUX) are the result of many processes. A mulch layer forms at soil surface if evaporation losses are not fully replenished. Actual evaporation is found by matching maximum vapour flux through the mulch layer (VAPFLUX) and the rate of upward water flow to the lower boundary of the mulch layer (WATSUPPLY) with the maximum rate of evaporation (EM). VAPFLUX is calculated from the vapour pressure gradient (between the mulch layer and the rooting zone) and diffusion coefficients. WATSUPPLY is calculated as vertical flow ; EM is calculated by correcting the evaporation rate from a bare soil for shading by the crop canopy. The actual rate of evaporation, EA, is found by matching the supply side, given by WATSUPPLY or VAPFLUX (whichever has the smaller value), with the demand EM. The smaller value is retained as the actual rate of water vapour loss.

The gross rate of water supply to the upper boundary of the rooted soil compartment (GROSSUP) is equal to precipitation plus irrigation, diminished by the actual evaporation losses of water from the soil surface. This gross supply enters the mulch layer; any surplus constitutes the net rate of water supply to the underlying root zone (NETSUP).

Infiltration of surface supply into the soil is conditioned by the soil's infiltration capacity (IM), which is determined by matric forces and gravity forces. NETSUP is matched with the momentary infiltration capacity. Excess supply increases surface storage of water for future release to the rooting zone (DS); or is lost by surface runoff (SR). Runoff occurs only when the surface storage capacity (SSC) is exceeded. SSC represents the equivalent water layer that can be stored on top of the land and is a function of the slope and surface properties of the land.

The flux through the upper boundary of the rooted soil compartment is solved by the equation:

```
UPFLUX = NETSUP + DS - SR
```

The result of the water budget equation, i.e. the rate of change in volume fraction of moisture in the root zone (RSM), can now be calculated with:

```
RSM = (UPFLUX + (CR - D) - TR) / RD
```

The equivalent rooting depth (RD) varies from a initial value at the beginning of the growing season till a maximum value reached when root growth ceases (RDSroot). Between these two limits, the increase of rooting depth over time is assumed linear (DeltaRD).

The initial values of all state variables at the beginning of the crop cycle are defined. For each time interval (Dt) they are then adjusted with the results of the water budget calculations:

```
soil moisture  : (new)SMPSI = (old)SMPSI + RSM * Dt
soil suction   : (new)PSI as function of (new)SMPSI
phreatic level : (new)ZT = (old)ZT + DeltaZT
surface storage: (new)SS = (old)SS - DS * Dt
rooting depth  : (new)RD = (old)RD + DeltaRD
```

Essential (pedo)transfer functions in this water balance model are those defining:

a. Moisture retention by the soil
   $SMPSI = SMO * PSI^{-GAM*ln(PSI)}$

b. Hydraulic conductivity of the soil
   KPSI = KO * EXP(-ALFA * PSI) at low suction
   $KPSI = AK * PSI^{-n}$ at high suction
   where the boundary between low and high suction is given by PSImax.

c. Vertical flow of water in the soil
   Flow = KPSI * (PSI gradient/ Distance - 1)

d. Infiltration of water in the soil
   $IM = SPSI * Dt^{-0.5} + Ktr$
   with SPSI = SO * (1 - SMPSI / SMO)

where

PSI	is matric suction of rooted soil (cm).
SMO	is total pore fraction ($cm^3.cm^{-3}$).
GAM	is texture-specific constant (cm^{-2}).
SMPSI	is volume fraction of moisture in soil with suction PSI ($cm^3.cm^{-3}$).
KPSI	is hydraulic conductivity of soil with matric suction PSI ($cm.d^{-1}$).
KO	is saturated hydraulic conductivity ($cm.d^{-1}$).
ALFA	is texture-specific geometry constant (cm^{-1}).
AK	is texture-specific empirical constant ($cm^{-2.4}.d^{-1}$).
n	is empirical constant, in practice n = 1.4 for all soil materials.
PSImax	is texture-specific suction boundary (cm).
SO	is reference sorptivity ($cm.d^{-0.5}$).
SPSI	is actual sorptivity ($cm.d^{-0.5}$).
Ktr	is hydraulic permeability of transmission zone ($cm.d^{-1}$).

Nutrients requirement for target production

In production situation PS3, production and yield are not quantified as outcome of calculations but are postulated. A target production is defined, equal to or less than the production potential at the PS2 level.

The crop takes up nutrients for growth and for storage. To achieve the target production extra nutrients may be required, above the nutrients supplied by the soil.

The nutrient budget of the rooting zone is extremely complex; it is the result of supply of nutrients, loss of nutrients and inactivation of nutrients. Nutrients are supplied by mineralization of organic matter, weathering of soil material, atmospheric deposition, autotrophic and symbiotic fixation, application of manure and fertilizers. Loss of nutrients is caused by leaching, volatilization, erosion, uptake, etc. Inactivation of nutrients is brought about by binding to compounds of low solubility, fixation to soil material and by antagonisms between elements. To simplify, three processes are considered: 1) supply of nutrients by the soil itself, 2) supply of nutrients with fertilizers, and 3) losses related to the application of fertilizers.

The nutrient requirement represents the difference between what the crop requires to meet the target production (the nutrient uptake requirement, NUR), and the quantity of nutrients that is provided by the soil itself (the base uptake, BU). The difference between these two quantities must be bridged by application of fertilizer(s). The efficiency of fertilizer use is expressed by the fraction of all fertilizer nutrients that is recovered by the crop (the recovery fraction, RF).

Growing plants maintain minimum concentrations of specific nutrient elements. These are differentiated for the yield and for the straw, and differ with crop type (grain crops, oil seeds, root crops and tuber crops). Uptake beyond these minimum concentrations ('luxury consumption') does not result in more product, but may lead to a better quality product. Indicative data on the minimum concentrations of nutrient elements in straw and in yield for a specific crop (group) are available.

The identification of elements in short supply is best done by plant tissue analysis (in the absence of identifiable deficiency symptoms). This has the disadvantage that the damage is already done. The model follows a different approach. It considers range of maximum and minimum nutrient concentrations. The range of nutrient concentrations is co-determined by the element ratios. The P/N ratio for instance varies only between 0.04 and 0.15. At a P/N ratio of 0.04, phosphorus is in short supply and inhibits further uptake of nitrogen. A P/N ratio of 0.15 signifies that nitrogen is in short supply which inhibits further uptake of phosphorous. The nutrient uptake requirement (NUR) for each element is calculated assuming minimum element concentrations in target yield and straw.

The yield-uptake relation for each nutrient element is assumed linear for yields less than the potential. Beyond this point, uptake requirement is met, and more uptake will not result in more yield. The slope (dY / d(UPTAKE)) of the element uptake-to-yield curve is calculated as the ratio between the potential dry yield at the PS2 scenario (no nutrient limitation) and the nutrient uptake requirement.

The nutrients provided by the inherent soil fertility support the 'Control Yield' realized on unfertilized land (CY). The nutrients supplied consist in part of nutrients carried over from past fertilizations in the crop rotation used.

The base uptake of nutrients from natural soil fertility (BU) is calculated by dividing the observed control yield (CY) by the calculated dY / d(UPTAKE) angle. Inhibited element uptake because of nutrient imbalance is taken into account by assuming induced N-shortage at real P-shortage, and vice versa.

The efficiency of nutrient(s) uptake from fertilizer(s) varies with fertilizer(s) selection and mode of application. The fertilizer recovery fraction (RF) is strongly influenced by management, e.g. by the selection or combination of fertilizers, and by the timing of fertilizer application. For elements other than phosphorus it is assumed that an RF value of 0.5 can be realized by a 'modal' farmer.

In the case of phosphorus, the RF depends very much on the soil material. RF values vary between 0.3 for an inert soil material such as quartzitic sand to 0.02 for an allophane-rich volcanic material.

Nutrients have to be available at the right place and time; the mode and timing of fertilizer application (MODE) influence efficiency. RF-values are modified from 0.9 times the listed recovery for broadcast, single applications to 1.5 if the fertilizer is placed in the vicinity of the roots.

All calculations are made on nutrient element basis. Conversion to fertilizers is obtained by dividing nutrient needs by the nutrient concentrations of the fertilizer(s) applied (NUTCONT).

In summary the fertilizer requirement (FR) is calculated for each nutrient element in each fertilizer as:

```
FR = (NUR - BU) / (NUTCONT * RF * MODE)
```

The steps taken in the calculation of fertilizer requirements are then :
a. Calculate the nutrient uptake requirement.
b. Calculate the yield-to-uptake angle.
c. Calculate the base uptake of a specific element.
d. Identify/estimate the efficiency of fertilizers application and uptake.
e. Calculate the fertilizer requirement.

4.2. New developments in modelling sunflower

Phenology

The phenology of a plant refers to its morphological appearance at any stage of plant development. Plant development of sunflower is linked with the number of leaves during vegetative growth and by development of the inflorescence during reproductive growth

(CETIOM, 1992; Schneiter and Miller 1981).

The time required for full development of the sunflower plant varies with genotype and environment (Schneiter and Miller, 1981). Differences in genotype are classified on the basis of plant height, uniformity of development, dry matter production and distribution (yield and oil content), resistance to pests and diseases, and nominal length of the growing period. All varieties, tall or short, high yielding or not, early or late, have almost the same phenology. Differences in environment, e. g. between sites, sowing dates or years, affect the durations of the various growth stages as well as yields.

Understanding of phenological responses of cultivars is essential for identifying (i) possible differences in growth and yield caused by environmental factors, and (ii) cultivars most suited to particular environments.

In modelling of sunflower growth there is a need to simplify and quantify the phenology description. One must pay attention to the most important stages in crop development and match field observations with model output. The analysis must be quantified to enable comparison of different environments and varieties.

The difference between daily temperature and a threshold temperature for development is used to quantify the duration of each development phase. Differences in these durations correlate with differences in precocity among varieties. For sunflower, differences in the heat sums at flowering, maturation and harvest, exist between varieties.

In the model, characteristics of the genotype determine the values of TSUM (the heat requirement for full plant development, °C.d), TLEAF (the heat requirement for full leaf development, °C.d), RDSroot (the relative development stage at which root growth ceases), SLA (the specific leaf area $m^2.kg^{-1}$) and fr(org) (the mass fraction of assimilates allocated to plant part 'org'). When characterizing sunflower phenology, the time scale is normalized; RDS = 1, at full development, and the duration of development phases is expressed as a relative fraction. SLA is quantified as a function of development stage. Other plant morphological characteristics such as leaf numbers, stem height, head diameter, root depth and moisture content of the tissue give further clues to phenological development.

The model that was developed for quantified land evaluation purposes simulates dynamically the state of the land-use system between emergence and maturity. This is the period of active growth. Emergence is characterized by the plant having its first pair of true leaves (after its cotyledons); maturity stands for physiological maturity, reached when the storage organ attains its maximum weight while the leaf area index decreases quickly to a value less than one. At this point the crop could be harvested but artificial drying would be needed to achieve a seed moisture content of 10 %. The periods between sowing and germination and the ripening off phase are not included in the calculations. The period between sowing and emergence depends on many factors including seed vigour, threshold temperature for germination, soil texture, structure, bulk density, colour, moisture content and soil temperature. Modelling germination requires many input data that are not readily available. Ripening off, i.e. the period between maturity and harvest, is the time when the standing crop loses moisture until it is dry enough to be harvested. The calculation of the ripening period is based only on weather parameters and is not included in the simulation.

In summary, attention for phenology in the dynamic simulation of crop growth helps to describe crop development and permits to better account for differences between varieties.

Characterization of phases

Successive partial harvests at fixed intervals during the growing season permitted to determine the dry masses of four plant parts: root, stem, leaf and storage organ. These data can be plotted against the relative development stage as shown in Fig. 4.1 where organ masses were normalized with the greatest mass equal to one. In Fig. 4.1, data on root mass were made negative only to make the graph more expressive.

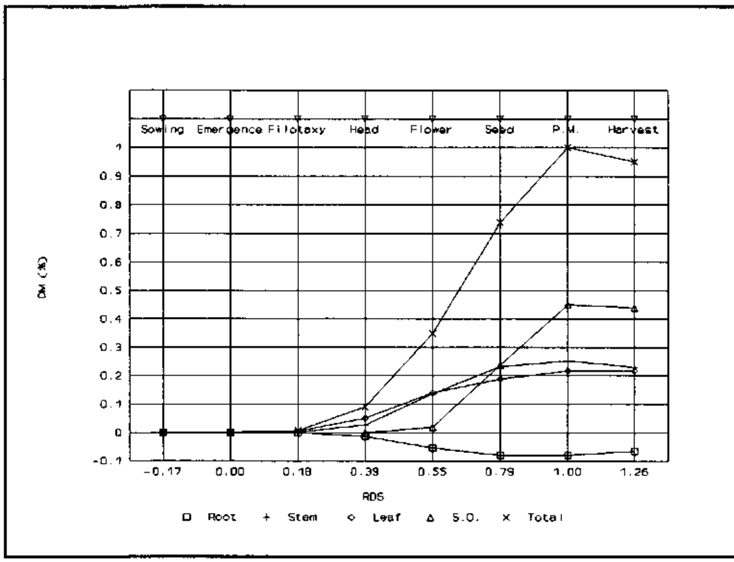


Fig. 4.1. Dry matter distribution relations for sunflower.

It is proposed here to adopt a simplified description of the sunflower growth stages suggested by Schneiter and Miller (1981). The description:

1. refers to a field crop instead of single plants,
2. makes accurate distinction at field level, without the use of microscopic observations and with use of broad levels such as 50 % anthesis, 80 % anthesis and so on,
3. defines classes that permit to distinguish clearly and unambiguously between varieties,
4. uses descriptors that are insensitive to differences imposed by the environment such as water stress,
5. integrates phenology descriptions in the model.

With the above in mind, observations were done at sowing, emergence, change in phyllotaxy, appearance of the head, appearance of an open flower, appearance of seed, physiological maturity and harvest. These correspond with the phases of 'germination', 'establishment', 'leaf expansion', 'head expansion', 'flowering', 'maturation' and 'ripening'.

The observation boundaries are identified as follows. Germination has occurred when the plants have their first true leaf pair (approximately four centimetres long). The change in phyllotaxy (i.e. when the plant changes from opposite to alternate leaves) happens at the third or fourth leaf pair. Head appearance is reached when a small head of one centimetre diameter is visible. Flower appearance is reached when an open flower appears. Seed appearance is reached when the first seeds have formed. Physiological maturity is reached when the storage organ attains its maximum dry weight. Sowing and harvest are self explanatory, whereby harvest is expected to take place when the seed moisture content is around 10 %.

Water stress affects growth period durations, as well as the durations of each phase. This is particularly evident in anthesis which normally proceeds centripetally towards the head's centre; plants suffering from water stress will not complete the process. This is the reason why an observation boundary was suggested only at the appearance of the first seeds.

Field observations of phenological maturity can hardly be precise. A clue to maturity is given by the discolouring of the head's backside. By then, the moisture content of the head has dropped significantly, and the leaves have turned yellow, whereas assimilates production has virtually stopped. This means that the leaf area index falls quickly; the remaining leaf area can just cover maintenance costs but no more weight is built up by the storage organ. For this reason 'physiological maturity' is set at the maximum storage organ weight.

Although a simplification, this classification still considers many plant characteristics whose importance is greater than just an indication of general phenological stages.

Source-sink relationships may explain other striking phenomena that occur over the growth period. Data from Fig. 4.2 indicates relative dry matter partitioning (root, stem, leaf and storage organ) over the development period.

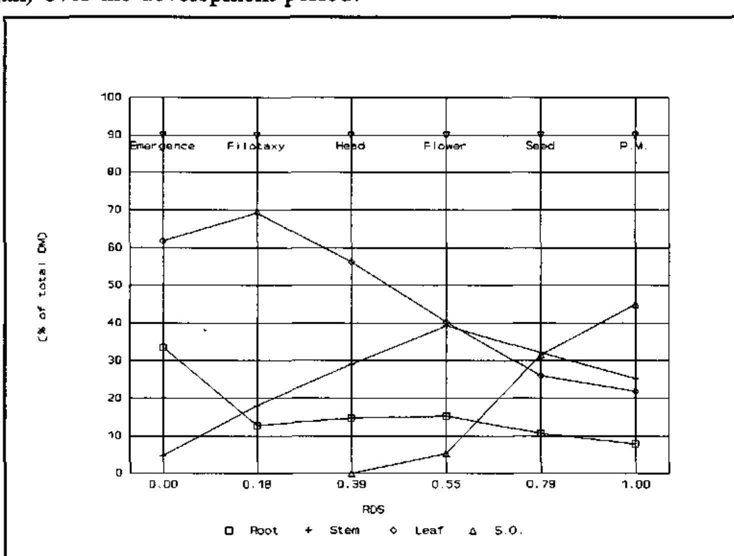


Fig. 4.2. Relative dry matter partitioning in sunflower.

Fig. 4.2 shows relative dry matter partitioning over the growing season. It presents the relative dry masses of plant organs.

It is striking that although the 'Head' stage marks the beginning of allocation of assimilates to the storage organ, this allocation becomes significant only at the boundary point 'Flower'. In terms of dry matter distribution and partitioning this later boundary marks a fundamental change in assimilate management, so that the full growing cycle could be roughly divided in two stages only. The appearance of the head marks the end of the vegetative stage of plant development and the beginning of the reproductive stage (Schneiter and Miller, 1981). This means that although the plant is not mature in terms of reproduction, the presence of these organs mark the start of reproductive growth. Integration of phenology makes that only two stages are required to describe sunflower development; the other phases serve as indicators for monitoring crop development.

The phenology of sunflower is summarized in Table 4.1. The durations of the various phases are expressed in terms of relative development stage, temperature sums and (ranges of) days. Important rates and values of phenology-related parameters are shown. Ranges in some of these parameters (can) indicate differences among varieties.

Table 4.1. Phenology-related parameters of sunflower over the growing season.

PHASE:	GERMIN	ESTABL	L.EXPAN	H.EXPAN	FLOWER	MATURAT	RIPENING
(R) (S) (L) (H)				(R) (S) (L)	(H)		
(Rd) (Sh) (Lm) (RDSr) (TLeaf)					* (Lm) * (RDSr)	* (TLeaf)	
TSUM	160	140	270	210	410	440	510
Days	17	18	21	17	24	21	26

	Sow.	Emer.	Fil.	Head	Flower	Seed	PM	Harv.
(Rd) (Sh)					* (Rd)	* (Sh)		
(Hd)		-	-	-	6	16	16	16
(dL)		0	0	1	2	4-6	8-10	13-15
(Lnr)		1	4-5	9-10	13-15	13-15	13-15	13-15
(MC)		90	90	90	90	90	75	10
RDS	-0.17	0.00	0.18	0.39	0.55	0.79	1.00	1.26

Where: (R) is maximum rate of root mass increment ($kg.d^{-1}$).
(S) is maximum rate of stem mass increment ($kg.d^{-1}$).
(L) is maximum rate of increment in leaf area ($cm^2.d^{-1}$).
(H) is maximum rate of increment in head diameter ($cm.d^{-1}$).
(Rd) is maximum root depth (cm).
(Sh) is maximum stem height (cm).
(Lm) is maximum LAI.
(RDSr) is where RDSroot is reached (end of root growth).
(TLEAF) is where TLEAF is reached.
(Hd) is head diameter (cm).

(dL) is number of dead leaf pairs.
(Lnr) is number of total leaf pairs.
(MC) is moisture content of the entire plant (%).

The values in Table 4.1. are indicative; differences in environment or variety may change the value of any parameter. This is particularly obvious in the case of the head diameter.

Examining the durations of the various phases in the two years of experimentation led to the notion that the transition between phases is striking only at flower initiation. Differences in temperature sums before and after that period show that development proceeds in two phases with distinctly different rates.

How phenology is affected by water stress is still unclear. When comparing the calculated temperature sums of stress-free and stressed plants, it becomes clear that the cycle of the latter is shorter. This implies that a correction has to be made to account for faster development under conditions of water stress. This correction is based on the assumption that the canopy temperature is higher than the air temperature under water stress.

The rate of phenological development seems to be greatly affected by temperature and/or radiation. In some varieties of sunflower, development is further influenced by the photoperiod. Climate conditions such as frost could abort crop growth. Fig. 4.3 was drawn using averaged daily weather data from Seville (from 1965 to 1995) and shows the number of days between planting and emergence calculated for emergence at different times in the year. Note that night frost may occur between December and March and that harvesting is hindered by moist weather from October on.

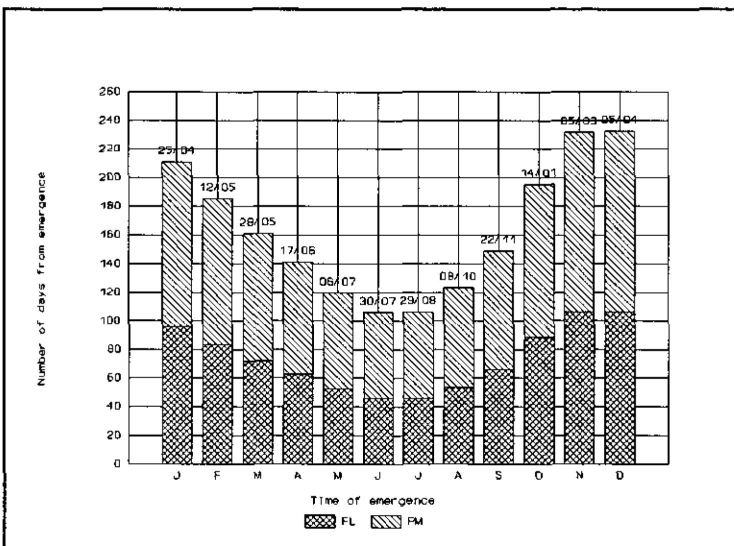


Fig. 4.3. Periods from emergence to flowering (**FL**) and to physiological maturity (PM).

The dates above each bar indicate when the crop could be harvested if emergence had take place at the beginning of the month. The graph clearly shows the most favourable timing for sunflower production (mid summer with the highest temperature/radiation).

Dry matter partitioning

In photosynthesis, assimilates are formed by reduction of atmospheric carbon dioxide to carbohydrates. These assimilates are then distributed to the various plant organs where maintenance requirements are met through respiration. The remaining sugars are converted to structural plant matter. Leaves are thus the source of assimilates, and roots, stems, storage organ and again leaves constitute sinks.

Crop characteristics required for modelling of crop growth include information on the partitioning of newly formed sugars over the various plant parts in the course of the season. Assimilates partitioning varies, inter alia, as a function of the relative development stage (RDS). An example of RDS-to-fr(org) relations is shown in Table 4.2, that presents assimilate fractioning in sunflower for seven points in the crop cycle, between RDS = 0 (emergence) and RDS = 1 (physiological maturity).

Table 4.2. Indicative RDS-to-fr(org) relations for sunflower.

RDS	Root	Stem	Leaf	S.O.
0.00	0.20	0.19	0.61	0.00
0.11	0.18	0.19	0.63	0.00
0.19	0.17	0.21	0.62	0.00
0.35	0.15	0.31	0.53	0.01
0.55	0.12	0.31	0.35	0.23
0.80	0.00	0.00	0.13	0.87
1.00	0.00	0.00	0.00	1.00

E.g. at RDS = 0.35, 15 % of the total assimilate production goes to the roots, 31 % goes to the stems, 53 % to the leaves and 1 % to the storage organ. If fr(org) is nil, the plant organ is either not yet formed (as is the case with the storage organ during vegetative growth phases), or is no longer functioning (as may be the case with other plant organs near the end of the growth cycle).

If plants react to environmental influences, then changes in the (relative) distribution of assimilates over the various plant organs would reflect the plant's priorities at any moment in time. Plant production models are in conflict with this notion if they typify assimilate allocation on the bases of few tabulated fr(org)-RDS combinations.

Plotting the RDS-fr(org) information in Table 4.2 yields the patterns of Fig. 4.4.

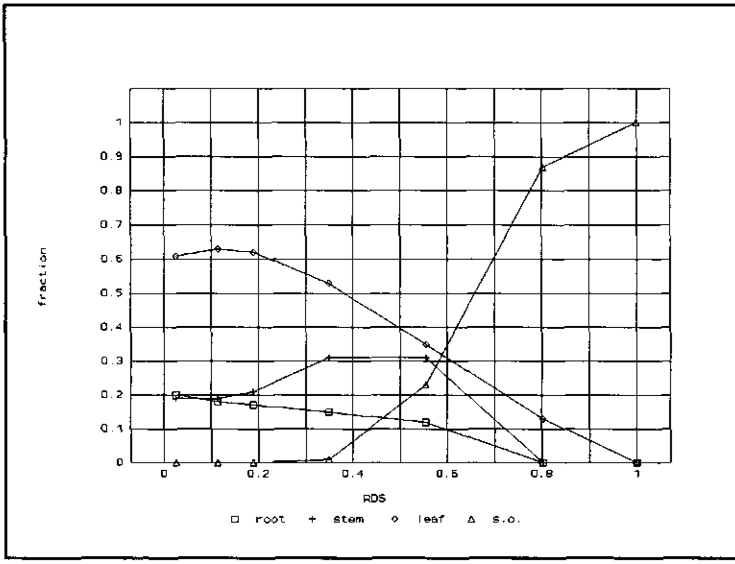


Fig. 4.4. Relative distribution of assimilates in sunflower, as a function of RDS.

Using tabulated assimilates fractioning entails a number of flaws:

1. tabulated allocation fractions are exogenous; any relation with other crop characteristics remains hidden.
2. there is no correlation with phenology. Fractioning values cannot be adjusted to conform with observed organ growth.
3. the plant is supposed to be indifferent to unfavourable environmental conditions.

The idea that a plant behaves logically when managing its assimilates, suggests that balance is maintained between the various plant organs. It does not make sense for a plant to invest in luxuriant leaf growth when there is insufficient available water to cover the associated (high) transpiration losses. Or why would a plant invest assimilates in the growth of massive stems if it has to support only small leaf and storage organ masses?

The hypothesis of logical plant behaviour was tested along the following lines:

1. construct the formal table, on the basis of literature research and own observations.
2. translate the table into analytical expressions of RDS-fr(org) relations.
3. introduce these equations in dynamic modelling and test their validity.

Data on assimilate fractioning over the growing season are collected through repeated harvesting of experimental fields. Data on the leaf area, phenology and morphology of sunflower were gathered for several fields near Seville, Spain, in 1993 and 1994.

As the identified analytical relations are based on partial harvests, they represent aggregate values valid for the period between two harvests. In crop growth simulation however, fractioning has to be calculated for each day in the growth cycle. To compare observed and calculated fractioning values, the model output has to (be aggregated to) cover the same periods as elapsed between the partial harvests.

Computing assimilate fractioning

Plant dry matter is formed through out the growth cycle of the crop. The rates of assimilation, maintenance respiration and growth respiration are continually changing. To compute the quantities of assimilates allocated to each plant organ between partial harvests, one must quantify gross assimilation and the compounded losses to maintenance and growth respiration between harvests.

It is tacitly assumed that assimilates formed are immediately allocated to the various plant organs where they are used for maintenance and growth. Actual increments in organ masses weights as recorded in partial harvests represent the net assimilate production between harvests multiplied by the efficiency of conversion.

The main steps in the quantification of the dry organ masses produced are the following (Driessen and Konijn, 1992):

1. Calculate assimilate production (Fgass in $kg_{sugar}.ha^{-1}.d^{-1}$).

2. Allocate assimilates to each plant organ.

```
GAA(org) = Fgass * fr(org)                                    (4.1)
```

where
fr(org) is mass fraction of Fgass assigned to organ 'org'.
GAA(org) is gross availability of assimilates to the organ ($kg_{sugar}.ha^{-1}.d^{-1}$).

3. Calculate maintenance respiration losses in each organ (MRR(org) in $kg_{sugar}.ha^{-1}.d^{-1}$).

```
MRR(org) = S(org) * r(org) * Cf(temp)                         (4.2)
```

where
S(org) is dry mass of living plant organ ($kg_{dm}.ha^{-1}$).
r(org) is organ-specific relative maintenance rate ($kg.kg^{-1}.d^{-1}$).
Cf(temp) is temperature correction factor (-).

4. Calculate the increment in dry mass of each organ (DWI in $kg_{dm}.ha^{-1}$).

```
DWI(org) = [GAA(org) - MRR(org)] * EC(org) * Dt               (4.3)
```

where
EC(org) is efficiency of conversion ($kg_{dm}.kg^{-1}_{sugar}$).
Dt is length of interval (d).

5. Calculate cumulative dry organ masses (S(org) in $kg_{dm}.ha^{-1}$).

```
(new)S(org) = (old)S(org) + DWI(org)                          (4.4)
```

If the interval between two successive harvests is sufficiently short, linear interpolations between the dry organ masses is permissible.

In the above sequence of calculations, fractionings (fr(org)) are input. To calculate fractionings from observed organ growth, the order of the operations has to be rearranged as follows:

1. First, S(org) is determined.
   When using data from partial harvests, the 'old' weight of each organ is referred as Si(org) instead of (old)S(org). Sf(org) is used instead of (new)S(org) to denote the value of S(org) at the next harvest.

2. DWI(org) is calculated with equation (4.4).

3. MRR(org) is calculated with equation (4.2).

4. GAA(org) is calculated with equation (4.3).

5. Fgass is then the sum of all GAA(org).

6. fr(org) is calculated on the basis of equation (4.1).

In the course of the growing season, Sf(org) may become less than Si(org). The following alternatives apply:

a. When DWI(org) is greater than MRR(org). Then, GAA(org) is zero.
   Respiration and allocation take place at the same time.

b. When GAA(org) is nil, it is assumed that allocation has stopped. Only respiration goes on.

c. When GAA(org) is equal to MRR(org), allocation only covers respiration losses.

Five alternative methods to compute allocation fractions have been explored; they differ in the use of organ-specific relative maintenance respiration rates (r(org)), the temperature correction factor (Cf(temp)) and the accountancy of assimilates production:

```
method 1 : Weather data required to compute Cf(temp).
           r(org) data used.
           assumption : if Sf(org) < Si(org) and DWI(org) < MRR(org)
                           then GAA(org) = 0
                        if SUMSf < SUMSi then fr(org) = 0 but fr(s.o.) = 1

method 2 : Same as method 1 but here Cf(temp) = 1.
           No weather data required.

method 3 : No weather data required (Cf(temp) = 1).
           r(org) data used.
           Assumption : if Sf(org) < Si(org) then GAA(org) = 0

method 4 : No weather data required (Cf(temp) = 1).
           r(org) data used.
           Assumption : if Sf(org) < Si(org) then GAA(org) = MRR(org)

method 5 : No weather data required (Cf(temp) = 1).
           No r(org) data used.
```

```
Use the data from partial harvests.
Assumption : fr(org) is distributed according to the differences
             in dry weight of each organ.
```

All these options are included in computer program FRAC.BAS (in Annex D). To run this program, two data files are needed: a weather file with site-specific data on maximum and minimum temperatures (file M.DAT in Annex C), and a file with data on partial harvests, notably date, RDS, LAI and dry matter weights for each plant organ (file X.DAT in Annex D).

The program uses data from every two consecutive harvests to compute indicative fractionings for the period between harvests using several methods. The data from the weather file are needed to compute day length and daily temperature fluctuation. Crop data needed include relative maintenance respiration rates (referred to in the output as 'Maintenances') and the efficiencies of assimilate conversion to structural plant (organ) matter (referred to in the output as 'Conversions'). The output of the program is illustrated by Table 4.3.

Table 4.3. Fractionings of sunflower c.v. Florasol computed with several methods.

Maintenance requirements : Root= 0.01, Stem= 0.075, Leaf= 0.05, S.O.= 0.023
Conversion efficiencies : Root= 0.71, Stem= 0.71, Leaf= 0.71, S.O.= 0.59
Data from Coria del Rio, 1993. Latitude (degrees) : 37.28

4.4.1. Harvest dates: days 95 & 109 (mean 102); RDS= 0.07; LAI= 0.01
Phenological phase: Establishment.

Organs	fr1 (-)	fr2 (-)	fr3 (-)	fr4 (-)	fr5 (-)	Rate (kg/d)	Sf/Si (-)	Si (-)	Sf
Root	0.23	0.23	0.23	0.23	0.26	0.4	6.0	0.20	0.25
Stem	0.17	0.18	0.18	0.18	0.21	0.3	5.0	0.20	0.21
Leaf	0.60	0.60	0.60	0.60	0.53	0.7	4.3	0.60	0.54
S.O.	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.00	0.00
total	1.00	1.00	1.00	1.00	1.00	1.4	4.8	1.00	1.00

4.4.2. Harvest dates: days 109 & 123 (mean 116); RDS= 0.15; LAI= 0.05
Phenological phase: Establishment.

Organs	fr1 (-)	fr2 (-)	fr3 (-)	fr4 (-)	fr5 (-)	Rate (kg/d)	Sf/Si (-)	Si (-)	Sf
Root	0.13	0.13	0.13	0.13	0.15	0.6	2.5	0.25	0.18
Stem	0.24	0.24	0.24	0.24	0.30	1.3	4.6	0.21	0.27
Leaf	0.63	0.63	0.63	0.63	0.56	2.4	3.6	0.54	0.55
S.O.	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.00	0.00
total	1.00	1.00	1.00	1.00	1.00	4.4	3.5	1.00	1.00

4.4.3. Harvest dates: days 123 & 144 (mean 133); RDS= 0.27; LAI= 0.58
Phenological phase: Leaf expansion.

Organs	fr1 (-)	fr2 (-)	fr3 (-)	fr4 (-)	fr5 (-)	Rate (kg/d)	Sf/Si (-)	Si (-)	Sf
Root	0.16	0.17	0.17	0.17	0.18	15.5	22.7	0.18	0.18
Stem	0.33	0.34	0.34	0.34	0.39	33.0	31.2	0.27	0.39
Leaf	0.49	0.49	0.49	0.49	0.41	34.7	16.5	0.55	0.42
S.O.	0.01	0.01	0.01	0.01	0.01	0.7	0.0	0.00	0.01
total	1.00	1.00	1.00	1.00	1.00	83.9	21.7	1.00	1.00

4.4.4. Harvest dates: days 144 & 166 (mean 155); RDS= 0.45; LAI= 1.63
Phenological phase: Head expansion.

Organs	fr1 (-)	fr2 (-)	fr3 (-)	fr4 (-)	fr5 (-)	Rate (kg/d)	Sf/Si (-)	Si (-)	Sf
Root	0.13	0.13	0.13	0.13	0.15	34.8	3.2	0.18	0.16
Stem	0.33	0.34	0.34	0.34	0.42	95.5	3.9	0.39	0.41
Leaf	0.29	0.29	0.29	0.29	0.19	42.7	2.2	0.42	0.25
S.O.	0.24	0.25	0.25	0.25	0.24	53.9	80.0	0.01	0.18
total	1.00	1.00	1.00	1.00	1.00	226.9	3.7	1.00	1.00

4.4.5. Harvest dates: days 166 & 187 (mean 176); RDS= 0.68; LAI= 2.03
Phenological phase: Flowering.

Organs	fr1 (-)	fr2 (-)	fr3 (-)	fr4 (-)	fr5 (-)	Rate (kg/d)	Sf/Si (-)	Si (-)	Sf
Root	0.00	0.00	0.00	0.03	-0.30	-19.0	0.6	0.16	0.09
Stem	0.00	0.00	0.00	0.05	-0.34	-21.8	0.8	0.41	0.29
Leaf	0.21	0.20	0.00	0.22	-0.17	-10.9	0.9	0.25	0.18
S.O.	0.79	0.80	1.00	0.70	1.80	116.1	3.0	0.18	0.44
total	1.00	1.00	1.00	1.00	1.00	64.4	1.2	1.00	1.00

4.4.6. Harvest dates: days 187 & 202 (mean 194); RDS= 0.90; LAI= 1.33
Phenological phase: Maturation.

Organs	fr1 (-)	fr2 (-)	fr3 (-)	fr4 (-)	fr5 (-)	Rate (kg/d)	Sf/Si (-)	Si (-)	Sf
Root	0.00	0.00	0.00	0.03	0.36	-10.2	0.78	0.09	0.07
Stem	0.00	0.00	0.00	0.08	0.95	-26.7	0.83	0.29	0.25
Leaf	0.00	0.00	0.00	0.33	0.36	-10.2	0.90	0.18	0.17
S.O.	1.00	1.00	1.00	0.56	-0.68	19.1	1.08	0.44	0.50
total	1.00	1.00	1.00	1.00	1.00	-28.0	0.95	1.00	1.00

where:

Harvest dates	are day in the year.
fr1 to fr5	are the fractionings calculated according to methods 1 to 5.
Si(x) and Sf(x)	are recorded initial and final partial dry matter masses of plant organ x.
Rate (kg/d)	is the rate of dry matter increase between harvests. Rate (kg/d)=(Sf(x)-Si(x))/(DATE(Harvest+1)-DATE(Harvest))
Sf/Si (-)	is the ratio of final and initial partial organ masses.

IF Sf(x) - Si(x) <> Sf(x) THEN RatioSfSi = Sf(x)/Si(x) ELSE RatioSfSi=0

Dry matter build-up varies markedly over the growth cycle of the crop:
1. Initially there is an increase in the weights of all vegetal organs and of the total plant.
2. Then there is a decrease in the weight of some organ(s) but an increase in total dry mass.
3. Finally there is a decrease in the weight of some organ(s) and in total dry mass.

Situation 1 applies during the major part of the growing season.
Situation 2 occurs when assimilation is reduced by dying off of leaves. Accumulation of (converted) sugars in the storage organ is then the main feature, sufficient to maintain an increase in total dry mass.

Situation 3 occurs near the end of the crop cycle, when assimilation is (almost) nil. Organs weights decrease and only the storage organ has a Sf/Si ratio greater than one. The point of physiological maturity is reached when the storage organ attains its maximum mass.

Table 4.3 shows that there is a great difference between method 5 and all other methods. Maintenance costs are not taken into account in method 5. The method is certainly not fit to describe situations where there is a decrease of dry matter. Taking only dry matter weights into account does not bring satisfactory results.

The remaining four methods will be compared in pairs. Methods 1 and 2 give almost identical results which suggests that the influence of the temperature is only slight. Evaluating dry matter production and distribution for the period when dry matter is decreasing, one observes that fractioning to the storage organ may change but it is unlikely that the fraction itself decreases. If the plant matures and assimilation decreases, the assimilates made can only be directed to the storage organ.

The second pair, methods 3 and 4, give exactly the same results as long as the dry masses are increasing. Beyond this point, differences are considerable; in method 3, available assimilates are set equal to nil if there is a decrease in organ dry matter. Whereas method 4 sets the available assimilates equal to the maintenance costs (there is always some partitioning to all plant organs in method 4).

Methods 1 and 2 seems to describe fractioning adequately. As the crop growth model already calculates the daily course of temperature and the temperature correction factor, method 1 is preferred. This choice had still to be confirmed by running the full crop growth simulation model.

Plotting the assimilate fractions obtained by method 1 yields Fig. 4.5 that was calculated with organ mass data from the two years of experimentation. The weather and harvest data used are in Annex C as weather file M2.DAT and in Annex D as partial harvest file X2.DAT.

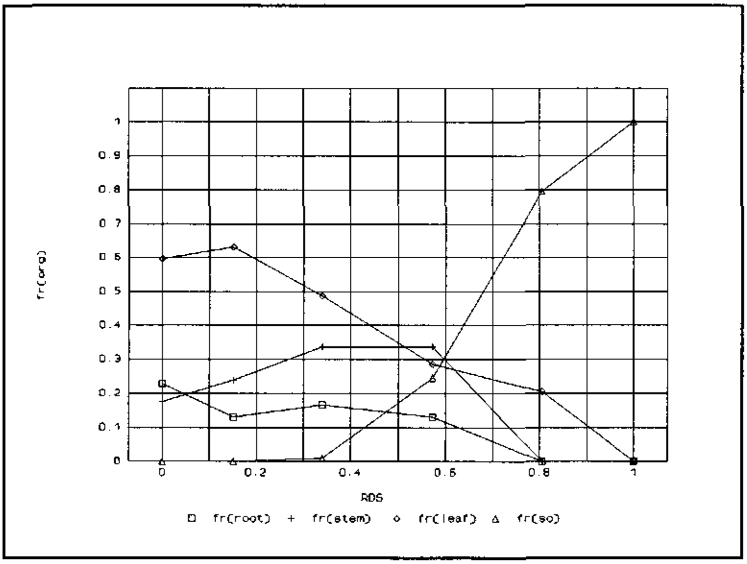


Fig. 4.5. RDS-to-fr(org) relations reconstructed using method 1.

Evidently, transitions of phenological stages do not necessarily have to happen at the time of the partial harvests. It would be an improvement to incorporate the phenological phases in the reconstruction of assimilate allocation. Setting the transition points first and correct the calculated fractionings afterwards leads to the (estimated) fractionings shown in Table 4.4.

Table 4.4. RDS-to-fr(org) relations for sunflower.

Phase	RDS	Root	Stem	Leaf	S.O.
Emergence	0.00	0.20	0.19	0.61	0.00
	0.11	0.18	0.19	0.63	0.00
	0.19	0.17	0.21	0.62	0.00
Flowering	0.35	0.15	0.31	0.53	0.01
	0.55	0.12	0.31	0.35	0.23
	0.80	0.00	0.00	0.13	0.87
Maturity	1.00	0.00	0.00	0.00	1.00

Plant organ ratios

It is obvious that the reconstructed fractioning values should result in calculated plant organ masses that are the same as found by partial harvesting. The next three figures present organ (mass) ratios as a function of RDS. Fig. 4.6 shows the Leaf/Root-ratio, Fig. 4.7 the Leaf/Stem-ratio and Fig. 4.8 the Shoot/Root-ratio. Curves A, B and C refer to different sunflower varieties. The figures were constructed using two years of data.

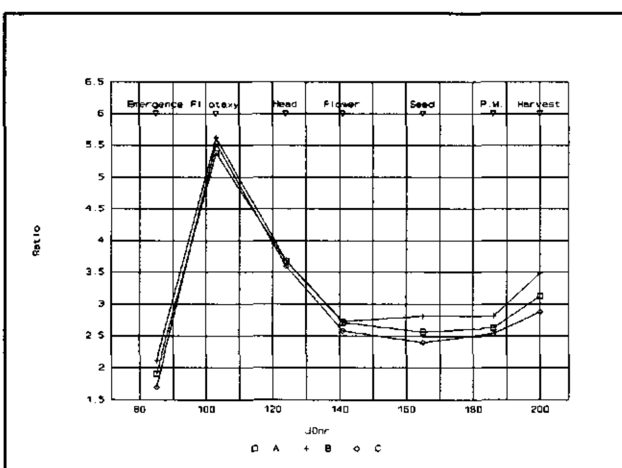


Fig. 4.6. RDS-to-Leaf/Root-ratio for sunflower.

Note that the Leaf/Root-ratio decreases steadily from an early peak to reach a much lower but steady value after flowering.

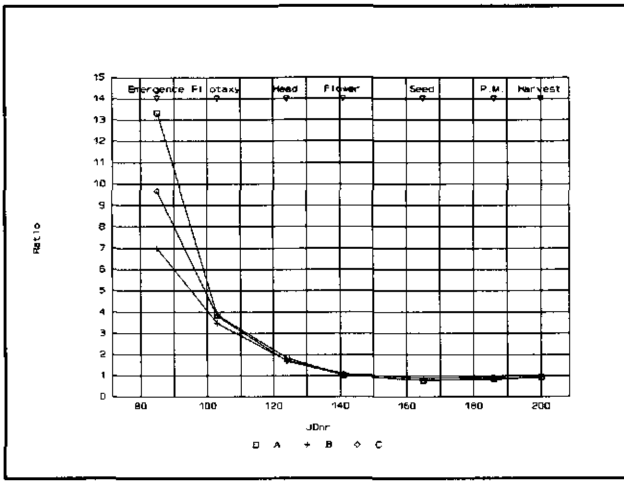


Fig. 4.7. RDS-to-Leaf/Stem-ratio for sunflower.

Likewise, the Leaf/Stem-ratio decreases to reach a steady value after flowering. In both cases the decrease seems to reflect the changing importance of the plant organ with ongoing development.

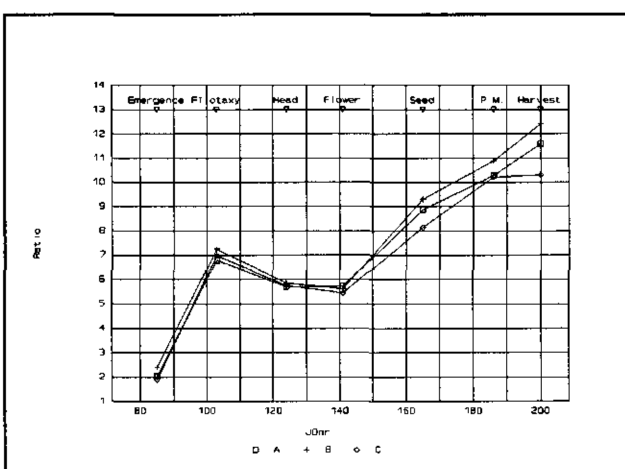


Fig. 4.8. RDS-to-Shoot/Root-ratio for sunflower.

The Shoot/Root-ratio (Fig. 4.8) seems rather stable between emergence and flowering and increases towards physiological maturity, in line with the accumulation of assimilates in the storage organ.

Ratios of dry organs and leaf mass suggest a more consistent crop development pattern than the tabulated fractionings.

To describe the ratios, the following set of equations was derived:

Storage organ/Leaf-ratio (soLf):

```
soLf = -1.4 + 3.5 * RDS                                          (4.5)
  if RDS < 0.40 then soLf = 0
```

Stem/Leaf-ratio (StLf):

```
StLf = 2 * RDS                                                   (4.6)

If StLf > 1.1 then StLf = 1.1
```

The Root/Leaf-ratio (RootLeaf) is constant at 0.35.

Dependent fractioning

In practice, the growing season is divided in two periods, with a transition at the time when the storage organ appears. This occurs at RDSso, when the storage organ/Leaf-ratio first assumes a value > 0. Root/Leaf-ratio is constant and Stem/Leaf-ratio depends on RDS, with a ceiling value defined by the maximum Stem/Leaf-ratio.

At the start of the calculations, the dry mass of seed or planting material used must be known. The initial dry organ masses are calculated as follows:

```
R/L + S/L + L/L + so/L = TDM / L
```

using the ratios at RDS = 0:

```
0.35 + 0.11 + 1 + 0 = TDM / L = 1.46 / L
```

Substitute the quantity of seed used (corrected for mortality), assuming that 1/3 of the gross seed input (SEED) is respired in germination:

```
initial Leaf mass = L = 0.67 * SEED / 1.46 = SEED / 2.18
```

The other initial organ masses are calculated with the ratios:

```
initial Stem mass = S = L * 0.11
initial Root mass = R = L * 0.35
initial SO mass = so = 0
```

The initial dry mass of the living leaves (LivSLeaf) is equal to total leaf mass (SLeaf). This value is used to calculate the initial LAI and the gross rate of assimilate production.

Fractioning estimation

Fractioning of the gross assimilate production to individual plant organs (frStem, frRoot and frSO) is now conditioned by fractioning to the leaf mass (frLeaf). The following set of equations describes the procedure for frStem (the procedure is the same for the organs 'root' and 'storage organ'):

initial organ mass:

```
      SStem =     SLeaf * StLf
```

organ mass over the next interval:

```
   newSStem = newSLeaf * StLf
```

dry weight increment over this interval:

```
    DWIStem = newSStem - SStem
            = (newSLeaf - SLeaf) * StLf
            = DWILeaf * StLf
```

maintenance respiration over the interval:

```
    MRRStem = RStem * SStem
            = RStem * SLeaf * StLf
```

assimilates available in this interval:

```
    GAAStem = DWIStem/ECStem + MRRStem
            = (DWILeaf * StLf)/ECStem + RStem * (SLeaf * StLf)
```

fractioning of assimilates to the stems:

```
     frStem = GAAStem/Fgass
            = (DWILeaf * StLf)/(ECStem * Fgass) + (RStem * SLeaf * StLf)/Fgass
```

The full set of equations reads :

```
   frRoot = (DWILeaf*RootLeaf)/(ECRoot*Fgass)+(RRoot*SLeaf*RootLeaf)/Fgass
   frStem = (DWILeaf*StLf)/(ECStem*Fgass)+(RStem*SLeaf* StLf)/Fgass
   frSO   = (DWILeaf*soLf)/(ECSO*Fgass)+(RSO*SLeaf*soLf)/Fgass
   frLeaf = 1 - (frRoot+frStem+frSO)
```

When frLeaf changes, DWILeaf changes and all other fractionings change as well; the sum of all fractionings is always equal to 1.0.

Correct values are found in a number of iterations:

```
   frLeaf = 0.01                                    'Initial boundary

   Loop of calculations:
      calculate all other fr(org)-values            'fr(org)
      SUMfr = Sum of all fr(org)                    'SUM of fr(org)

      if SUMfr - 1 > 0.001 then                     'Loop condition
         newfrLeaf = 1 - (frRoot + frStem + frSO)   'Final boundary
         frLeaf = (frLeaf + newfrLeaf) / 2          'Closer to the solution
         goto Loop
      end Loop
```

when the loop condition (i.e. (SUMfr - 1) < 0.001) is met, the calculated fractionings are retained and used in the crop growth calculations.

A computer program to calculate fractionings as discussed is listed in Annex D (program D-FRAC.BAS). Output of this program is shown in Fig. 4.9.

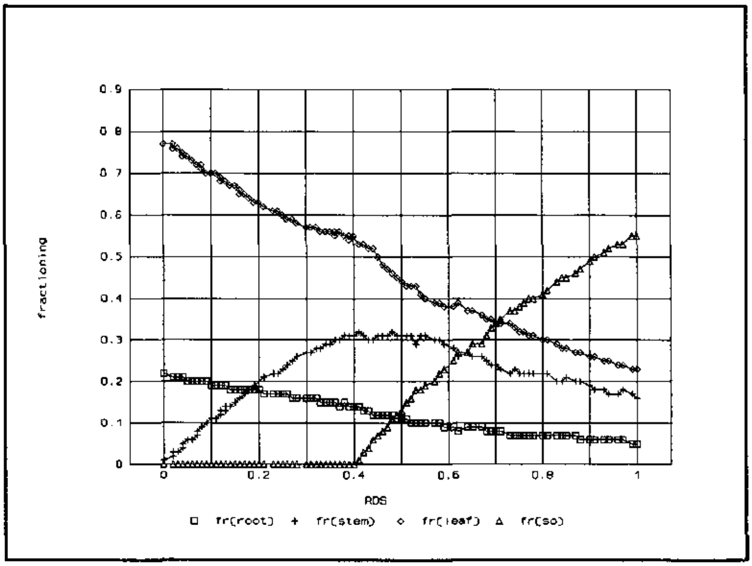


Fig. 4.9. Calculated fractioning factors.

AMAX (maximum rate of assimilation)

Under conditions of light saturation and optimum temperature, the rate of assimilation depends on the biochemical pathway of photosynthesis. The most important pathways are those referred to as C3 and the C4 after the length of the carbon chain of the first produced assimilate. Gross assimilation is reduced by photorespiration and dark respiration. Photorespiration is regarded as a process inefficiency, specific to C3-plants (Lövenstein et al., 1992).

Table 4.5 shows the main differences between the two photosynthetical pathways (Lövenstein et al., 1992).

Table 4.5. Characteristic values and ranges of crop assimilation.

Parameter	C3-plants	C4-plants
Optimum temperature	20 °C (15-25)	30 °C (25-35)
Photorespiration	35 %	0 %
Dark respiration	2	2
EFF	0.45 (0.45-0.45)	0.45 (0.45-0.40)
AMAX	40 (20-50)	60 (50-80)

Dark respiration and AMAX ($kg.ha^{-1}.h^{-1}$), EFF ($kg.ha^{-1}.h^{-1}$ / $J.m^{-2}.s^{-1}$).

Light response curves relate radiation with gross assimilation, at specified temperature. These curves are fully described by two parameters: the light use efficiency at low intensity (EFF) and the maximum rate of assimilation at light saturation (AMAX) (De Wit et al., 1978).

EFF is the initial slope of the light response curve. Here, light is the limitation factor, and assimilation rates are not strongly affected by temperature At light saturation, the rate of assimilation increases with temperature until an optimum temperature is reached. The value of EFF is reported by various authors (quoted by van Heemst, 1988) and lies between 0.45 and 0.50. For simulation purposes, EFF is set to a value of 0.5 $kg.ha^{-1}.h^{-1} / J.m^{-2}.s^{-1}$.

AMAX represents the maximum (gross) rate of assimilation at light saturation, it indicates the plateau of the light response curve. Photorespiration and temperature determine the level of AMAX. Photorespiration lowers the efficiency of assimilation; consequently the levels of AMAX are different for C3 and C4-plants as reported in Table 4.5.

The effect of temperature is expressed by the AMAX-to-temperature response curve. The optimum temperature for assimilation differs by (group of) crops and is not steady.

Plants appear to adapt to prevailing temperatures. Consequently, a reference temperature (to which the plant 'got used') is defined to better estimate the actual value of AMAX. AMAX-to-temperature relations for C3-plants, such as sunflower, have been approximated as:

```
AMAX = 1.8 * Tref - 0.15 * (Tref - Tday)²                          (4.7)

where
Tday is daytime temperature (°C)
Tref is reference temperature (°C), defined as the weighted averaged
        daytime temperature over the past ten days, with a minimum of
        15 °C and a maximum of 30 °C.
```

Equation (4.7) describes a parabolic curve with a minimum AMAX value of 27 (for Tref = Tday = 15 °C) and a maximum of 54 (for Tref = Tday = 30 °C). The optimum temperature for assimilation would be between 25 and 30 °C.

The difference between the reference temperature and the daytime temperature ranges over the growing season from a maximum 6.1 °C to a minimum -4.6 °C, with corresponding differences in AMAX of 8.7 to -5.4 $kg.ha^{-1}.h^{-1}$.

Daytime temperature refers to the average temperature during the day, when the plant assimilates. It is normally somewhat higher than the daily (24 hours) average temperature. The corresponding difference in AMAX ranges between 2 and -2 $kg.ha^{-1}.h^{-1}$.

Assimilation by a crop varies over the growing period, due to variations in light availability and light interception. Light availability varies with (the time of) the day, the day in the year and the latitude of the site. Light interception is a property of the crop and depends on canopy properties.

Spitters (1986) defines the gross rate of CO_2-reduction, as follows:

```
Fgc = DL * (AMAX/Ke) * ln[(AMAX +CC)/(AMAX + CC * EXP(-LAI * Ke))]  (4.8)

with CC = EFF * Ke * PAR

where
Fgc  is  gross rate of CO2-reduction by a closed reference crop (kg.ha-1.d-1).
```

```
DL   is day length (h.d-1).
AMAX is maximum rate of assimilation at actual temperature (kg.ha-1.d-1).
Ke   is extinction coefficient for visible light (-).
LAI  is leaf area index (m2.m-2).
EFF  is light use efficiency at low light intensity (kg.ha-1.h-1 / J.m-2.s-1).
PAR  is photosynthetically active radiation (J.m-2.s-1).
```

The potential gross production of assimilates by a field crop, is then:

```
Fgass = Fgc * 30 / 44

where
Fgass   is gross rate of assimilate production by a field crop (kg.ha-1.d-1).
30/44   is ratio of molecular masses of CH2O and CO2.
```

The above equation is only valid if there is no shortage of water. Water stress will affect the rate of assimilation; a correction factor for suboptimum availability of water has to be introduced:

```
Fgass = Fgc * 30 / 44 * CFWATER
```

Assimilation is also affected by other factors such as leaf age, water status of the leaf, nitrogen status of the leaf, pests, diseases, etc. At potential production, all these factors are irrelevant except for leaf age. Leaves attain their maximum assimilatory capacity just after they are fully expanded. Very young leaves are not fully photosynthetically active; AMAX decreases also with leaf senescence.

Calculating AMAX

Two approaches are proposed to calculate the maximum rate of assimilation:
- a) one by relating measured/inferred crop assimilation with AMAX as described by equation (4.8),
- b) another based on the AMAX-to-temperature relations (equation 4.7).

Experimental data collected through partial harvests and field measurements, and simulation procedures provide the possibility to turn equation (4.8) around and calculate AMAX. Photosynthetically active radiation and day length are calculated, the extinction coefficient is measured, leaf area and dry plant organ masses are measured at different points in time.

The calculation procedure is based on the following reasoning:
1. The time interval is defined by two consecutive partial harvests.
2. Differences in organ masses and calculated maintenance respiration allow to quantify the gross rate of assimilate production (Fgass) in the interval.
3. Next, PAR and day length in the interval are averaged and converted to daily values.
4. The LAI value for the interval is the averaged LAI of the two harvests.
5. Use an iterative procedure to calculate 'real' AMAX.

Equation (4.8) is split in two parts: a left (LHS) and a right hand side (RHS), both containing the unknown variable AMAX. By iteration a value for AMAX is found which satisfies LHS = RHS, where:

```
LHS = (Fgc * Ke) / (DL * AMAX)
RHS = LOG ((AMAX + CC) / (AMAX + CC * EXP(-LAI * Ke)))
```

The main calculations follow these lines:

```
Fgass(org) = DWI(org) / (EC(org) * Dt) + MRR(org)
Fgass = Fgass(Root) + Fgass(Stem) + Fgass(Leaf) + Fgass(s.o.)
Fgc = Fgass * 44 / 30

'Compute AMAX by iterative procedure:
CC = EFF * Ke * PAR
AMAX1 = .01  'starting value
'
Iterate:
RHS = LOG((AMAX1 + CC) / (AMAX1 + CC * EXP(-LAI * Ke)))
AMAX2 = Fgc * Ke / (RHS * DL)
IF ABS(AMAX1 - AMAX2) < .001 THEN GOTO End of iterations:
AMAX1 = (AMAX1 + AMAX2) / 2: GOTO Iterate:
'
End of iterations:
AMAX1(Harvest) = AMAX1
```

The second approach requires the calculation of daytime temperature and a reference temperature.

Reference temperature is arbitrarily defined as the weighted daytime temperature over the last ten days, with weighing factors proportional to the time (in days) before the current day, and with boundaries of 15 and 30 °C.

Daytime temperature is calculated with equation (4.12).

With the calculated Tday and Tref values, an 'absolute' AMAX value can be approximated using equation (4.7). AMAX values lie between a maximum value of 88 $kg.ha^{-1}.h^{-1}$, assumed to be the maximum assimilation rate of any crop, and a minimum of 0.00001 to avoid calculated negative values.

Both approaches were included in a computer program; the results are shown in Fig. 4.10.

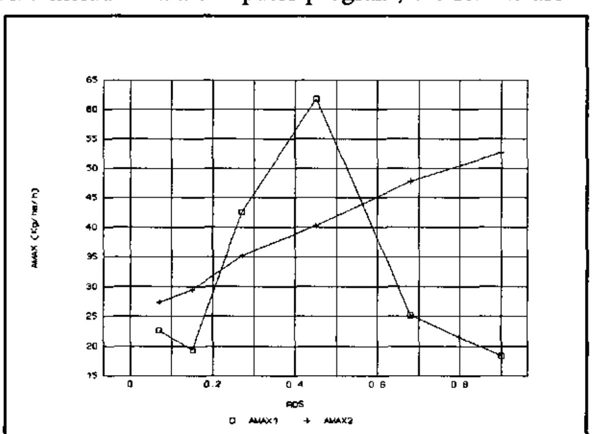


Fig. 4.10. Calculation of 'Real' AMAX (AMAX1 calculated from crop assimilation, and 'Absolute' AMAX2 from temperature).

The boundaries of AMAX1 in Fig. 4.10 agree well with common notion, as the minimum value is around 18 $kg.ha^{-1}.h^{-1}$ and the maximum around 62 $kg.ha^{-1}.h^{-1}$. The shape of the curve indicates a dependence on the LAI of the standing crop, with low values at the beginning and near the end of the growing season, and a maximum around the period of full development. AMAX2 shows the absolute assimilatory potential as a function of temperature development over the crop cycle.

Correcting AMAX1 and AMAX2 for the LAI of the standing crop, yielded the following graph (Fig. 4.11).

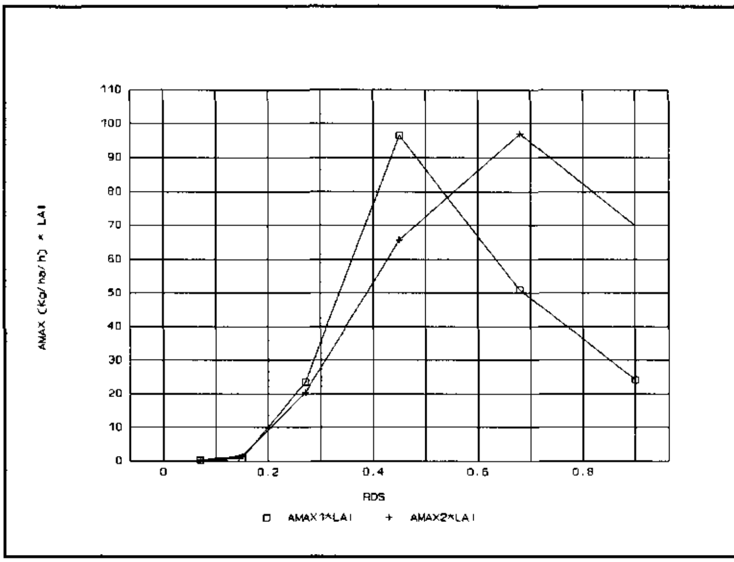


Fig. 4.11. AMAX1 and AMAX2 corrected for the LAI of the standing crop.

Fig. 4.11 shows the relative assimilatory potential at actual LAI over the crop cycle, with AMAX1 dependent only on the temperature and AMAX2 on all factors that influence assimilation and growth.

Temperature

Temperature influences crop growth, crop performance and crop behaviour, notably the duration of the growth cycle, the longevity of leaves, and the rates of assimilation and maintenance respiration.

Some of these effects occur only above a threshold temperature and/or are influenced by diurnal temperature fluctuations e.g. assimilation (takes place during daytime only) and maintenance respiration (during the entire day). The daily course of temperature has to be described.

The length of the growth cycle of a crop is primarily determined by the crop's 'heat requirement', TSUM in degree days. Crops that suffer from water stress during (part of) their growth cycle grow shorter, suggesting that their heat requirement is satisfied more quickly.

Daily maximum and minimum air temperature data are generally available. However air temperature may differ from the temperature of the crop. When there is no shortage of water and transpiration is not hampered, the canopy temperature is lower than the air temperature because the latent heat of vaporization causes the canopy temperature to drop. If there is shortage of water, the canopy temperature may become higher than the air temperature.

It stands to reason that not the air temperature determines the pace of crop development, but the canopy temperature.

Daily course of temperature

The daily course of the air temperature is roughly sinusoidal during daytime and exponential during the night. The minimum temperature is assumed to occur at sunrise. The day length, from sunrise to sunset, is a function of the latitude of the site and the day in the year.

Day length and air temperature are described by the following set of equations:

```
DL = 12 * (PI + 2 * ASIN(SSCC)) / PI                                  (4.9)

with  SSCC = SSIN / CCOS
      SSIN = SIN(LAT * RAD) * SIN(DEC * RAD)
      CCOS = COS(LAT * RAD) * COS(DEC * RAD)
      DEC  = -23.45 * COS(2 * PI * (Day + 10) / 365)

where DL  is day length, in h.d-1.
      PI  is 3.14159.
      LAT is latitude of the site, in degrees.
      RAD is PI / 180.
      DEC is declination of the sun.
      Day is day in the year (1 - 365).

Tsset  = Tmin + (Tmax - Tmin) * SIN(PI * (DL / (DL + 3)))             (4.10)
Tnight = (Tmin-Tsset*EXP(-(24-DL)/4)+(Tsset-Tmin)*EXP(-Time)          (4.11)
Tday   = Tmin+(Tmax-Tmin)*SIN(PI*(Time-12+DL/2)/(DL+3))               (4.12)
T24h   = (Tday * DL + Tnight * (24 - DL)) / 24                        (4.13)
Tavg   = (Tmax + Tmin) / 2                                            (4.14)

where Tsset  is air temperature at sunset, in °C.
      Tnight is night time air temperature, in °C.
      Tday   is day time air temperature, in °C.
      T24h   is equivalent 24-hours air temperature, in °C.
      Tavg   is average daily air temperature, in °C.
      Time   is solar time, in h.
```

Integrating equations (4.11) and (4.12) over the duration of the night and the day produces so-called equivalent temperatures. Integration is done using a 3 point Gaussian integration.

The various air temperatures calculated, arranged according to descending value, are the following:

```
Tmax > Tday > Tsset > Tavg >= T24h > Tnight > Tmin
```

Computer program DAYTEMP.BAS (in Annex D) performs these calculations. Results generated for Coria del Rio, 1994 are shown in Table 4.6.

Table 4.6. Equivalent temperature values generated for Coria del Rio, 1994. Latitude is 37.28 degrees N.

Month	DL	Tmax	Tday	Tsset	Tavg	T24h	Tnight	Tmin
1	9.75	15.7	12.8	12.2	10.4	9.3	6.8	5.0
2	10.60	16.8	13.7	12.7	11.1	10.1	7.4	5.5
3	11.75	23.4	19.2	17.3	15.9	14.9	10.8	8.3
4	12.97	23.0	18.9	16.5	15.7	15.2	10.8	8.4
5	14.00	25.1	21.7	19.4	19.1	18.9	15.1	13.1
6	14.52	32.2	27.6	24.3	24.1	24.0	18.6	16.0
7	14.28	36.8	31.5	27.7	27.4	27.3	21.0	18.0
8	13.40	34.1	29.4	26.6	25.9	25.4	20.4	17.7
9	12.21	29.5	25.1	23.0	21.7	20.9	16.5	13.9
10	10.99	25.3	22.3	21.2	20.0	19.1	16.4	14.6
11	9.97	22.1	19.2	18.7	17.0	15.9	13.6	11.9
12	9.48	16.8	14.2	13.8	12.1	11.1	9.0	7.4
MONTHLY								
max :	14.5	36.8	31.5	27.7	27.4	27.3	21.0	18.0
min :	9.5	15.7	12.8	12.2	10.4	9.3	6.8	5.0
DAILY								
max :	14.6	43.5	35.8	32.2	32.0	31.9	27.3	25.0
min :	9.4	10.0	7.2	6.7	4.8	3.5	0.3	-2.0
ANNUAL								
avg :	12.0	25.1	21.3	19.5	18.4	17.7	13.9	11.7
sum :	4380	9167	7789	7119	6722	6468	5076	4265

The table demonstrates that substituting average temperature (Tavg) for daily temperature (T24h) or daytime temperature (Tday) introduces errors.

Fig. 4.12 compares simulation data with measured hourly data. The labels 'avg', 'sim' and 'int' stand for daily average temperature (calculated as the mean from daily maximum and minimum temperatures), simulated daily average temperature (calculated in the procedure to compute T24h) and measured daily average temperature (the mean of hourly measured temperatures) respectively.

Fig. 4.12 shows the differences between measured and averaged daily temperatures (variable 'int-avg') and between simulated and averaged daily temperatures (variable 'sim-avg'), between the day numbers 118 (28 April) and 144 (24 May) for Coria del Rio, 1994.

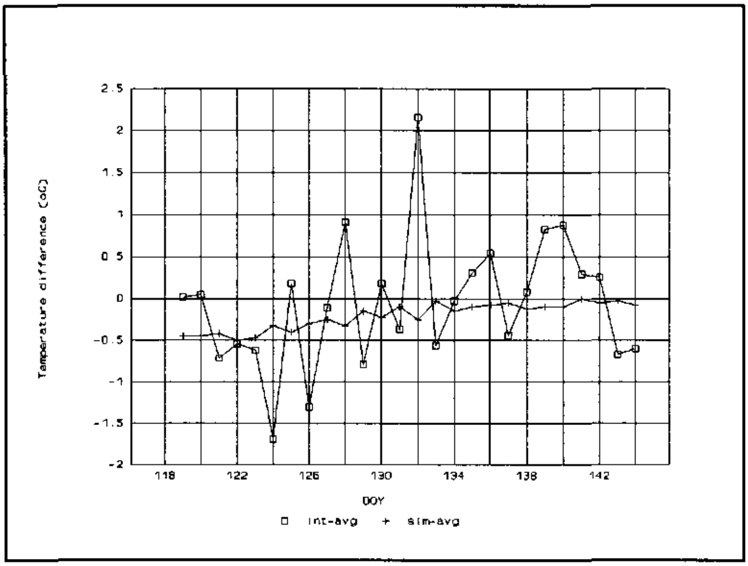


Fig. 4.12. Differences between average temperature and simulated (sim-avg) and measured (int-avg) daily air temperatures at Coria del Rio in 1994.

Canopy temperature

Incident radiation heats a canopy; transpiration cools a canopy. The incident radiation amounts to the total radiation income at canopy level corrected for reflection and long-wave losses. The evaporative heat loss incurred in transpiration is found by multiplying daily transpiration by the latent heat of vaporization. The momentary difference between air and canopy temperature was calculated with equations used by program SUNFLOR.BAS; the routine is listed in program TEMPDIFF.BAS (in Annex D).

The main equations are:

Difference between air temperature and canopy temperature (TDiff, in °C):

```
TDiff = (INTER - TRLOSS) / (HEATCAP * 1)   '"1" meter to satisfy dimensions

with
INTER  = (CANRAD * (1 - REFLCROP) - LWLOSS) * Dt
EXTRA  = SC * RDN * 3600 * DL
CANRAD = EXTRA * TRANS

where
INTER is net intercepted radiation (J.m-2.d-1).
EXTRA is extraterrestrial radiation (J.m-2.d-1).
SC    is solar constant (SC = 1353 J.m-2.s-1).
RDN   is fraction of SC at latitude 'LAT' and day 'DAY'.
TRANS is atmospheric transmission (0-1).
```

Evaporative heat loss incurred in transpiration:

```
TRLOSS = 10 * TRM * CFWATER * Dt * LATHEAT   (J.m-2)

with TRM = TR0 * CFLEAF * TC        'maximum transpiration rate (cm.d-1).
```

```
where
TRO    is potential transpiration rate (TRO = ETO(Day) - .05 * EO(Day).
CFLEAF is ground cover fraction of the canopy (CFLEAF=1-EXP(-Ke*LAIDay)))
TC     is actual turbulence coefficient (TC = 1 + (TCM - 1) * CFLEAF)
TCM    is maximum turbulence coefficient (from crop file)
```

Long-wave radiation losses:

```
LWLOSS = BOLTZ * (T24h+273)^4 * (.56 -SQR(VPA)*0.079)*(0.1+0.9 * SunH / DL)
```

Temperature values generated with program TEMPDIFF are in Table 4.7:

Table 4.7. Results of temperature simulation with TEMPDIFF.BAS.
Data of Coria del Rio, 1994. Latitude: 37.18 degrees N.

Day	DL	T24h	TDiff	TRANS	EXTRA	CANRAD	LWLOSS	INTER	TRLOSS
98	12.68	14.2	2.5	0.66	34.03	22.38	8.67	7.67	0.09
105	12.95	14.0	2.3	0.54	35.44	19.07	6.87	7.05	0.11
112	13.22	13.4	2.8	0.55	36.74	20.30	6.25	8.57	0.21
119	13.47	20.9	3.1	0.71	37.90	26.83	9.46	10.13	0.80
126	13.71	21.2	2.9	0.64	38.92	24.81	7.42	10.69	2.00
133	13.93	16.1	2.4	0.54	39.80	21.29	5.71	9.84	2.64
140	14.12	16.7	1.9	0.40	40.52	16.31	3.49	8.41	2.75
147	14.28	20.7	2.1	0.60	41.10	24.55	6.02	11.90	5.61
154	14.41	22.6	0.6	0.61	41.53	25.24	7.12	11.30	9.50
161	14.50	25.2	0.1	0.60	41.81	25.08	6.50	11.81	11.49
168	14.55	21.4	0.3	0.65	41.95	27.16	7.13	12.70	11.67
175	14.56	25.4	-0.3	0.67	41.93	28.35	8.36	12.34	13.32
182	14.52	27.7	-1.1	0.63	41.78	26.14	6.85	12.23	15.53
189	14.44	28.5	-1.5	0.64	41.49	26.36	7.68	11.56	15.98
196	14.32	26.9	-0.0	0.67	41.05	27.58	7.95	12.18	12.26
201	14.22	28.2	0.5	0.69	40.65	28.08	8.51	11.98	10.43
min :	12.56	10.8	-2.3	0.23	33.39	9.43	0.76	5.68	0.04
max :	14.56	31.9	3.6	0.72	41.97	29.23	10.90	13.99	18.05
avg :	13.98	21.2	1.2	0.61	39.76	24.21	7.07	10.60	7.03

where
Radiation values are in $MJ.m^{-2}$
Labels min, max and avg refer to the period between days 95 and 202, 1994.

Soil temperature

Soil temperature influences biological, physical and chemical processes in soils. Germination of seeds (and the duration of the germination phase) is particularly dependent on soil temperature.

Soil temperature is determined by transport of heat in the soil and by exchange of heat between the soil and the atmosphere, which are dominated by meteorological conditions and strongly dependent on soil moisture content.

Soil temperature data are not always available; for land evaluation exercises the air temperature is often used instead.

Hourly air, soil and dew point temperatures were recorded automatically at Coria del Rio. Table 4.8 shows data for the period between 31 March and 30 June 1994. Soil temperature was recorded at 15 cm depth.

Table 4.8. Hourly air (TAir), soil (TSoil) and dew point (TDew) temperatures.

Stats	Date	TAir	TSoil	TDew
minimum :	31/03	3.4	13.8	-6.3
maximum :	30/06	38.5	23.2	19.2
average :	15/05	19.6	18.7	10.5
std.dev.:		6.8	2.5	4.4
c.v. (%):		35	13	43
sum :	92	43225	41210	23076

Over the entire period, the average air temperature differs from the soil temperature by 0.9 °C. Within this period two days were chosen on which extreme air temperature values were reached: the minimum value on April 17 and the maximum on June 29; the hourly course of the soil temperature is depicted on these 'extreme' days in the next two figures.

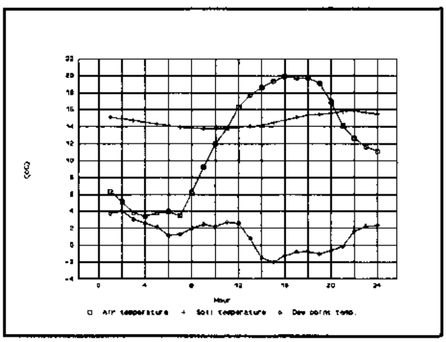


Fig. 4.13. Soil, air and dew point temperatures on 17 April 1994.

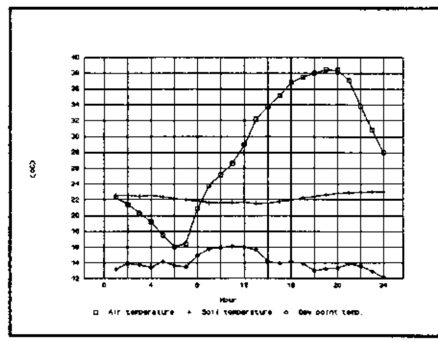


Fig. 4.14. Soil, air and dew point temperatures on 29 June 1994.

On some days, air and soil temperatures may be quite different:

	TAir	TSoil
April 17 :	12.0	14.7
June 29 :	28.3	22.2

Averaging the hourly data to daily data yielded the nfollowing graph of the seasonal course of daily temperatures at Coria del Rio, 1994.

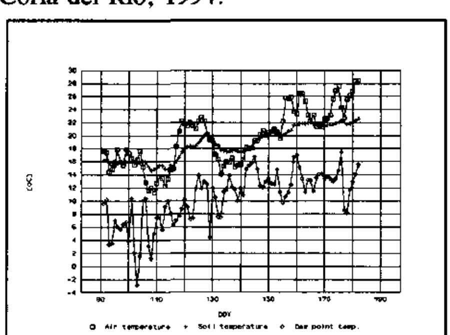


Fig. 4.15. Seasonal course of daily temperatures at Coria del Rio in 1994.

Note that the average air and soil temperatures are almost the same over a longer period, especially in the first part of the graph. Computing the duration of the germination phase with the air temperature does not seem to produce a disturbing error.

Dew point temperature

The occurrence of dewfall is important to water balance calculations. As data on dew point temperature are not always available, a procedure is tested to calculate the dew point temperature.

The measured data are air temperature (TAir), dew point temperature (TDew1) and relative air humidity (RHA), in Coria del Rio from day 91 to day 182. The calculation of the dew point temperature (TDew2) uses the following set of equations:

$$e_s = 6.107 * EXP(17.4 * TAir / (TAir + 239))$$
$$e_a = RHA * e_s$$
$$TDew2 = (\ln(e_a / 6.107) * 239) / (17.4 - \ln(e_a / 6.107))$$

where e_s is saturated vapour pressure (mbar).
e_a is actual vapour pressure (mbar).

The results are presented in Table 4.9, where differences between measured and calculated dew point temperatures are indicated as 'TDew2-Tdew1':

Table 4.9. Measured and calculated dew point temperatures.

Stats	TAvg	Tmax	Tmin	TSoil	TDew1	RHA	e_s	e_a	TDew2	diff
maximum :	28.5	38.5	20.5	22.6	17.5	0.88	39.0	21.0	18.3	3.1
minimum :	11.3	17.2	3.4	14.7	-2.9	0.27	13.4	5.1	-2.4	0.0
average :	19.6	27.0	12.1	18.7	10.5	0.61	23.6	14.1	11.6	1.1
std.dev.:	4.3	5.8	3.9	2.5	4.0	0.13	6.4	3.3	3.9	0.6
c.v. (%):	22	21	32	13	38	22	27	24	34	54

where 'diff' is TDew2 - TDew1.

For calculated and measured dew point temperatures, see Fig. 4.16. The calculated dew point temperature is always somewhat higher than the measured one. The R squared between them is 0.98.

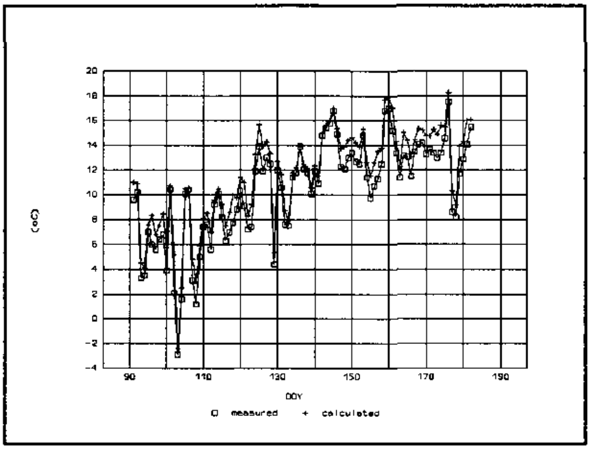


Fig. 4.16. Dew point temperatures (measured TDew1 and calculated TDew2) at Coria del Rio in 1994.

Radiation and evapotranspiration

The energy balance

The energy balance at soil surface is described by:

$$R_N - HEAT - LE - G = 0 \quad (J.m^{-2}.d^{-1}) \qquad (4.15)$$

where R_N is net radiation.
HEAT is sensible heat flux.
LE is latent heat flux.
G is soil heat flux.

The radiation that reaches the top of the atmosphere (EXTRA) varies with the latitude and day in the year. The fraction of EXTRA that reaches canopy level (TRANS) is determined by the atmospheric transmissivity. The incoming shortwave radiation (Radiat) at canopy level is then:

$$Radiat = EXTRA * TRANS \qquad (4.16)$$

When this radiation reaches a surface it is partly reflected, absorbed or transmitted. The albedo represents the fraction losses due to reflection. Net shortwave radiation is calculated as:

$$NetRadiat = Radiat * (1 - Albedo) \qquad (4.17)$$

Part of the net radiation is intercepted by the canopy, the rest is transmitted to the soil surface. As a rule of thumb, half the incoming NetRadiat is photosynthetically active radiation (PAR):

```
PAR = 0.5 * NetRadiat                                        (4.18)
```

The actual amount of absorbed radiation (ABSORBED) is calculated from the maximum available radiation (PAR).

The net longwave radiation (RLong) is a function of daily ambient temperature, actual vapour pressure and cloudiness.

The net radiation (R_N) is the difference between short and longwave radiation:

$$R_N = NetRadiat - RLong \quad (4.19)$$

The soil heat flux is estimated to be 10 % of the NetRadiat:

```
G = 0.1 * NetRadiat                                          (4.20)
```

The available energy for evapo(transpi)ration is calculated as:

$$NetEnergy = (R_N - G) \quad (4.21)$$

The sensible heat flux (HEAT) is the only unknown variable in equation (4.15).

Extraterrestrial radiation (EXTRA)

Extraterrestrial radiation is radiation that reaches the outer side of the atmosphere (Angot radiation). It varies with the latitude (LAT) of the site and day of the year (DAY). Accounting for the day length, one obtains a value for the daily extraterrestrial radiation. The day length (DL in $h.d^{-1}$) is calculated with:

```
DL = 12 * (PI + 2 * Atan(SSCC)) / PI                         (4.22)

with   SSCC = SSIN / CCOS

       SSIN = SIN(LAT) * SIN(DEC)
       CCOS = COS(LAT) * COS(DEC)
       DEC = -23.45 * COS(2 * PI * (DAY + 10) / 365)

where  DEC  is declination of the sun (°).
       SSIN is sine of latitude in radians.
       CCOS is cosine of latitude in radians.
       PI   is constant (PI = 3.14159).
```

The daily extraterrestrial radiation (EXTRA in $J.m^{-2}.d^{-1}$) is now found with:

```
EXTRA = SC * RDN * 3600 * DL                                 (4.23)

with  SC  = 1373 * (1 + .033 * COS(2 * PI * DAY / 365))
      RDN = (SSIN + 24 * CCOS * SQR(1 - SSCC * SSCC) / (PI * DL))

where SC   is solar constant corrected for the sun eccentricity (J.m-2.s-1).
      RDN  is fraction of the solar constant that arrives at a specific site.
           (LAT) during a specific day (DAY).
      3600 is conversion factor (from second to hour).
```

For Coria del Rio (latitude 37.2 ° North), the calculated values of EXTRA lie between a maximum of 42.0 $MJ.m^{-2}.d^{-1}$ and a minimum of 15.3 $MJ.m^{-2}.d^{-1}$, with an average of 29.3 $MJ.m^{-2}.d^{-1}$.

Atmospheric transmissivity (TRANS)

To arrive at the incoming radiation at canopy level (Radiat), radiation losses incurred in the atmosphere must be accounted for. Angström (1924) describes the transmissivity of the atmosphere (TRANS) as:

```
   TRANS = a + b * SunH(DAY) / DL                                   (4.24)

where a = 0.29 * COS(LAT)
      b = 0.52
      SunH(DAY) is number of sun hours on day DAY.
```

For Coria del Rio, year 1992, the measured ratio SunH/DL during the cropping season varied between a maximum of 0.97 and a minimum of 0.0; the average value was 0.70. There were 3097 sun hours with an average SunH of 8.5 $h.d^{-1}$. The cumulative day length amounted to 4380 hours, with a maximum of 14.6 $h.d^{-1}$, a minimum of 9.4 h d^{-1}, and an average of 12.0 sun hours per day. The equipment error is estimated at (less than) 10 % of measured SunH.

The atmospheric transmissivity over the same period varied between a maximum of 0.73 and a minimum of 0.23, with an average of 0.60. The limits for a de-facto 'clear' sky and an 'overcast' sky were set to 0.70 and 0.15 respectively. These limits will also be used to estimate the components of direct and diffuse radiation.

Net shortwave radiation (NetRadiat)

The net incoming shortwave radiation at canopy level is the incoming radiation diminished by the radiation that is reflected by the canopy (Albedo) as described by equations (4.16) and (4.17).

Shortwave radiation is composed of direct (Dir) and diffuse (Diff) radiation:

```
   Radiat = Dir + Diff                                              (4.25)
```

The calculation of daily direct and diffuse radiations is based on the relation between the fraction of diffuse radiation (FracDiff) and the atmospheric transmissivity (TRANS). This relation is described by three segments, separated by boundaries of TRANS at 0.70 and 0.15:

```
   if TRANS > 0.70 then FracDiff = 0.23                             (4.26a)
   if TRANS < 0.15 then FracDiff = 1.0                              (4.26b)
   ELSE FracDiff = 1.0 - 1.4 * (TRANS - 0.15)                       (4.26c)
```

It follows that:

```
Diff = FracDiff * Radiat                                          (4.27a)
Dir  = Radiat - Diff                                              (4.27b)
```

The values calculated for Coria del Rio, 1994, are shown in Table 4.10. Radiation variables are in $MJ.m^{-2}.d^{-1}$, TRANS and FracDiff are fractions.

Table 4.10. Direct and diffuse radiation values.

Values	Radiat	TRANS	FracDiff	Diff	Dir
maximum	29.1	0.73	0.89	10.9	22.2
minimum	3.6	0.23	0.23	2.5	0.4
average	17.6	0.60	0.38	5.9	11.8

Radiation makes plant growth possible. If radiation data are available, they can be entered in the weather file. Measured data and approximated radiation values for Coria del Rio (1994) have an R^2 of 0.89.

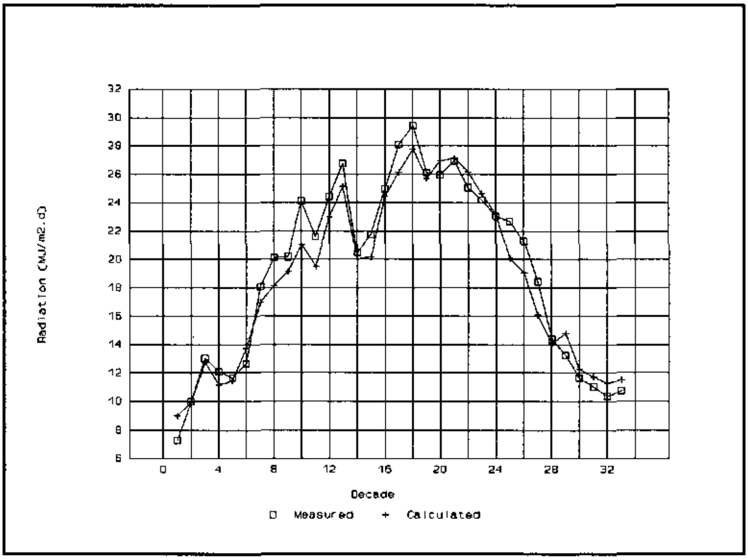


Fig. 4.17. Measured and calculated radiations at Coria del Rio in 1994.

Fig. 4.17. shows that the measured values are close to the calculated ones. The error incurred in estimating radiation values is less than 3%.

Net longwave radiation (RLong)

Net longwave radiation is a function of daily ambient temperature, actual vapour pressure and cloudiness:

```
   RLong = f(daily temperature) * f(actual vapour pressure) * f(cloudiness)
                                                                      (4.28)
where  f(daily temperature) = Boltz * (T24h(DAY) + 273) ^ 4
       f(actual vapour pressure) = (0.56 - SQR(EAct) * 0.079) (-).
       f(cloudiness) = (0.1 + 0.9 * SunH(DAY) / DL(DAY)) (-).
```

```
Boltz is Stephan-Boltzmann constant, equal to 0.0049 (J.m^-2.d^-1.K^-4)
EAct  is actual vapour pressure (mbar).
```

Substituting daily weather data from Coria del Rio, 1994, gives the following results:

Table 4.11. Calculation of net longwave radiation terms.

Stats	T24h	Tday	Tnight	Eact	SunH	DL	RLong	f(T)	f(VP)	f(S/DL)
maximum :	33.2	36.7	29.0	31.6	13.0	14.6	10.0	43.1	0.37	0.97
minimum :	3.0	7.9	-0.5	5.7	0.0	9.4	0.6	28.4	0.12	0.10
average :	17.5	21.0	13.8	15.6	8.5	12.0	6.4	35.0	0.25	0.73
std.dev.:	6.2	6.5	5.3	5.3	3.3	1.8	2.2	3.0	0.05	0.22
c.v. (%):	36	31	38	34	39	15	34	9	21	31

It appears that integrating separate day and night temperatures makes no significant difference to the value of f(T). Using an average T24h value changes the value of RLong by less than 0.2 %. Using T24h data straight away produces RLong-values that hold for a full day.

The limits of the vapour pressure term f(VP) are:

```
f(VP) = 0, (the minimum) for:
SQR(EAct) * 0.079 = 0.56 or EAct = 50.2 mbar. This happens only at
temperatures >50 °C.

f(VP) = 0.56, (the maximum) for:
EAct = 0 mbar. This never happens.
```

On cropped fields, these limits are never reached; extreme f(VP) values were 0.37 and 0.12 in 1992.

The limits of f(SunH/DL) are:

```
f(SunH/DL) = 0.1, (the minimum), for:
SunH = 0, on a completely overcast day.

f(SunH/DL) = 1.0, (the maximum) for:
SunH = DL, on a completely clear day (not recordable).
```

The extreme (SunH/DL) values were between 0.97 and 0.10 in 1992.

Fig. 4.18 shows how f(VP) and f(SunH/DL) at Coria del Rio changed over 1992.

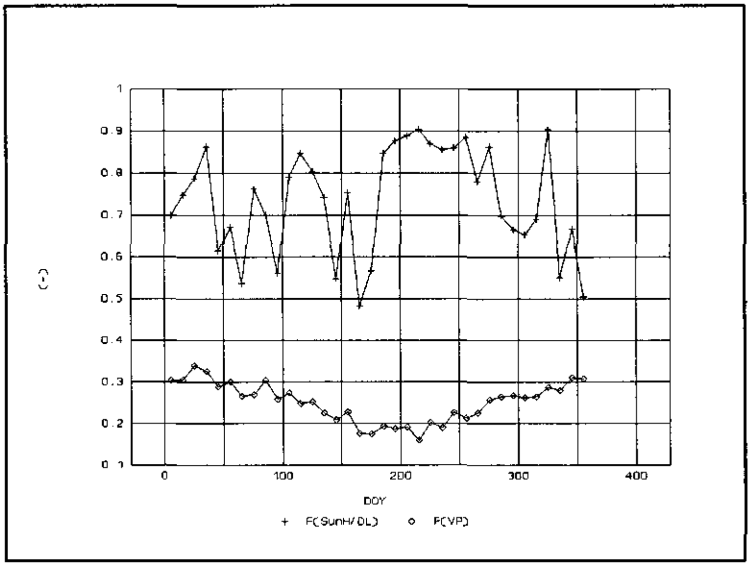


Fig. 4.18. Annual course of f(VP) and f(SunH/DL) at Coria del Rio in 1992.

Absorbed radiation (ABSORBED)

The 'absorbed radiation' term represents all PAR (photosynthetically active radiation) that the plant intercepts and absorbs for assimilates production ($J.m^{-2}.s^{-1}$).

Recall that the assimilation-to-radiation curve is described by two parameters: the initial light use efficiency at low light intensity (EFF = 0.5 $kg.ha^{-1}.h^{-1}$ / $J.m^{-2}.s^{-1}$), and AMAX, the maximum rate of assimilation at actual temperature ($kg.ha^{-1}.h^{-1}$). Actual assimilation depends further on intercepted radiation, which is a function of canopy architecture and leaf area:

```
INTERCPTD = (1 - EXP(-Ke * LAI)) * PAR                                  (4.29)
```

where the expression EXP(-Ke * LAI) represents the fraction of radiation throughfall. The intercepted radiation fuels photosynthesis. Theoretically, 8 quanta of light are needed for the reduction of one molecule of CO_2. The average energy content of a quantum is 210 $kJ.mole^{-1}$ and of a mole of CH_2O 470 kJ (Kropff and Spitters, 1991). This suggests an efficiency of radiation conversion of 0.28; the amount of absorbed radiation is expressed by:

```
ABSORBED =  470 / ( 8 * 210) * INTERCPTD                                (4.30)
```

Weather data from Coria del Rio, 1993, were used with the program SUNFLOR.BAS to calculate the biophysical yield potential of sunflower (emergence on day 96 and a sowing density of 5 kg ha^{-1}).

Table 4.12. Radiation use.

Stats	DL	AMAX	Fgc/DL	PAR	Tfall	II	IA	II/PAR	IA/PAR
maximum :	14.6	54	64	394	371	384	107	0.97	0.27
minimum :	12.6	24	0	365	10	1	0	0.00	0.00
average :	14.0	39	31	389	168	221	62	0.56	0.16
std.dev.:	0.6	8	25	8	153	159	45	0.40	0.11
c.v. (%):	4	20	82	2	91	72	72	72	72
total :	1470	4063	3241	40814	17629	23185	6486	59	16

For explanation of table see text.

Table 4.12 shows radiation use over the growing season. 'II' is intercepted radiation (INTERCPTD), 'IA' is absorbed radiation (ABSORBED) and 'Tfall' throughfall of radiation. The average absorbed radiation is 0.16 of PAR. With PAR set to 50 % of incoming radiation, the maximum efficiency of photosynthesis is 8 %.

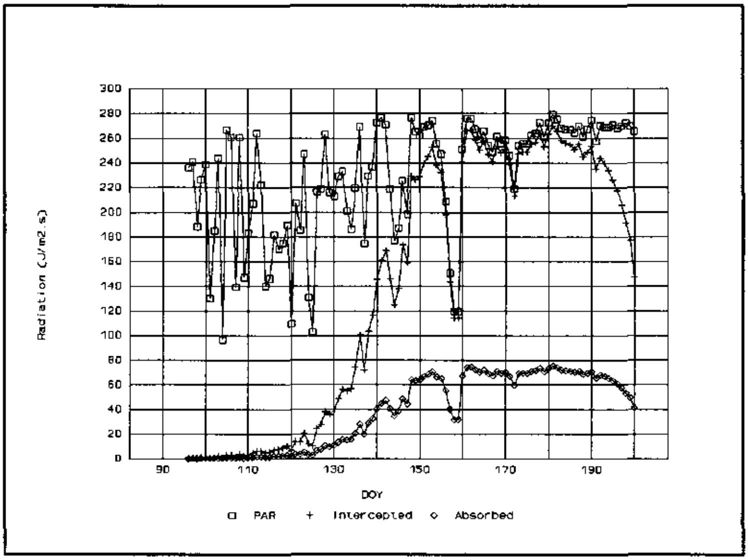


Fig. 4.19. Calculated daily course of PAR, intercepted and absorbed radiations for a sunflower crop in Coria del Rio, 1993, from day 96 onwards.

The averaged value of AMAX is 39. Assimilation follows the normal trend but there are points where actual assimilation (given by Fgc/DL) is greater than AMAX, due to a greater LAI value than the reference. Fig. 4.20 show how these figures evolve during the growing season.

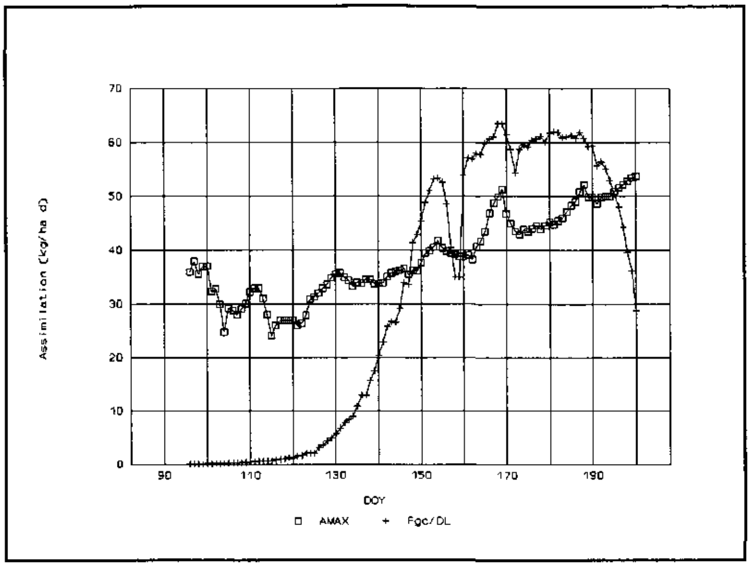


Fig. 4.20. Calculated daily course of AMAX and Fgc/DL for sunflower in Coria del Rio, 1993, from day 96 onwards.

The Penman-Monteith equation

Many meteorological stations publish values of potential evaporation (E0) and potential evapotranspiration (ET0). Where these data are not available they must be calculated.

The Penman-Monteith equation is widely used to compute potential evapo(transpi)ration from different surfaces: wet surface (E0); soil surface (Es); reference crop (ET0); or a specific crop (ETc). Usually a calculated ET0 is multiplied by a crop coefficient to obtain ETc (Doorenbos and Pruitt, 1984).

$$ETc = Kc * ET0 \qquad (4.31)$$

where Kc accounts for the compounded effects of all crop conditions different from the reference crop, e.g. the albedo, and the aerodynamic and crop resistances.

Evapotranspiration according to the Penman-Monteith equation:

$$L*E = \frac{s * (R_N - G) + \dfrac{\varphi_a * \epsilon * L * \gamma}{P_a} * \left(\dfrac{e^*(T_z) - e_z}{R_a}\right)}{s + \gamma * \left(\dfrac{R_a + R_c}{R_a}\right)} \qquad (4.32)$$

where ϵ is M_w / M_a = 0.623.
M_w is molar mass of water vapour.

M_a is molar mass of air.
γ is psychrometric constant (mbar.K^{-1}).
P_a is air pressure (mbar).
z is height of measurement (m).
φ_a is air density (kg.m^{-3}).
R_c is crop resistance (s.m^{-1}).
R_a is aerodynamic resistance (s.m^{-1}).
s is slope of the vapour pressure curve at T_z (mbar.K^{-1}).
L is heat of vaporization of water (J.kg^{-1}).
R_N is net radiation (J.m^{-2}.s^{-1}).
G is heat flux into the soil (J.m^{-2}.s^{-1}).
E is evapotranspiration (kg.m^{-2}.s^{-1}).
T_z is temperature at z (K).
e_z is actual vapour pressure at z (mbar).
e^* is saturated vapour pressure at T_z (mbar).

the same equation simplified:

$$L*E = \frac{R_a * s * NetEnergy + AUXIL * VPD}{s * R_a + \gamma * (R_a + R_c)} \quad (4.33)$$

where NetEnergy = $(R_N - G)$
AUXIL = $\varphi_a * \epsilon * L * \gamma / P_a$
VPD = $(e^*(T_z) - e_z)$.

The two main variables that condition evapotranspiration are radiation and air dryness:

$$L*E = RadTerm + DryTerm \quad (4.34)$$

where RadTerm = $R_a * s *$ NetEnergy / DENOM
DryTerm = (AUXIL * VPD) / DENOM
DENOM = $s * R_a + \gamma * (R_a + R_c)$.

Evaluating the respective contributions of RadTerm and DryTerm to total evapotranspiration using data of Coria del Rio, 1992, suggests that DryTerm contributes less than 0.001 % of RadTerm. The evapotranspiration of field crops in the area seems to depend entirely on radiation, and its accuracy varies with the accuracy of the net radiation estimation.

One alternative method (of many) to estimate ET0 would be the empirical Hargreaves (1985) "temperature range" method:

$$L * ET0 = 0.0023 * (Tavg + 17.8) * (Tmax - Tmin)^{0.5} * EXTRA \quad (4.35)$$

where Tavg is average of maximum (Tmax) and minimum (Tmin) daily air temperatures, and EXTRA is extraterrestrial radiation. The two temperatures are readily available, and EXTRA can be calculated simply and accurately. The square root of the daily temperature difference is correlated with actual radiation and relative air humidity.

Comparing Hargreaves's method with the Penman-Monteith equation for Coria del Rio 1992, yielded the patterns shown in next graph.

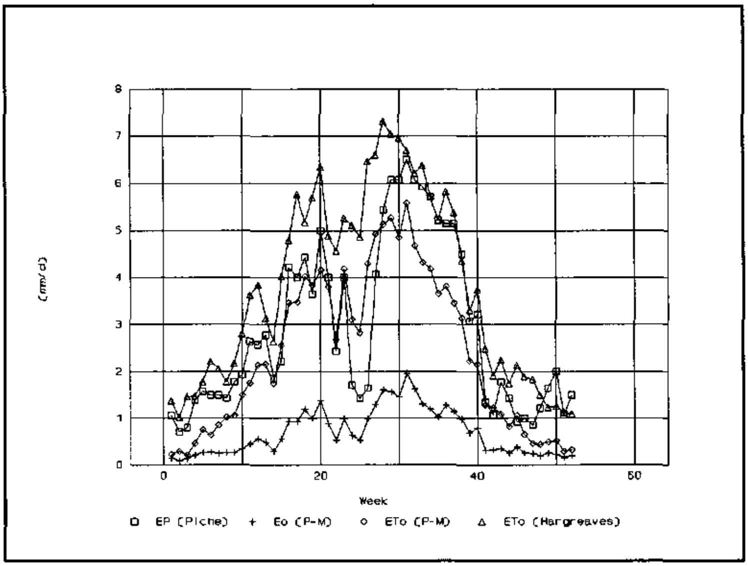


Fig. 4.21. Evapo(transpi)ration at Coria del Rio in 1992; comparison of Piche evaporation (EP(Piche)), Penman-Monteith E0 and ET0 (E0(P-M) and ET0(P-M)) and Hargreaves (ET0(Hargreaves)) values.

Note that the Hargreaves values correlate well with those calculated according to Penman-Monteith (R^2 = 0.97).

Net radiation (NetEnergy)

The net radiation term denotes the energy available for evapotranspiration. It is composed of net shortwave radiation, net longwave radiation and a soil heat flux. In earlier equations it was defined as NetEnergy = (R_N - G), with R_N = NetRadiat - RLong (equation 4.33).

Transpiration involves vaporization of water which is an endothermic process, that causes a disparity between canopy temperature and air temperature.

Air heat capacity (AUXIL)

The heat capacity of air (AUXIL in $J.m^{-3}.K^{-1}$) is calculated as :

```
   AUXIL = AirDen * Molar * LatHeat * Gamma / AirPres                    (4.36)
```

where AirDen is air density at T24h ($kg.m^{-3}$):

```
      AirDen = .348432 * AirPres / (T24h(DAY) + 273)

      AirPres is air pressure at T24h (mbar):
      AirPres = 1013 * EXP(-.034 * ALTITUDE / (T24h(DAY) + 273))

      Molar is molar mass ratio of water vapour over air = 0.623
```

```
LatHeat is latent heat of vaporization of water at T24h (MJ.kg-1):
LatHeat = (2.501 - (2.361 * .0001) * T24h(DAY)) * 10^6

Gamma is psychrometric constant at T24h (mbar.K-1):
Gamma = 1626 * AirPres / LatHeat.
```

For a particular altitude, the values of these parameters depend on the daily temperature. Table 4.13 shows some statistics on each term in the AUXIL calculation.

Table 4.13. Ranges in daily data collected in Coria del Rio in 1992.

Stats	T24h	AirPres	AirDen	LatHeat	Gamma	AUXIL
maximum :	33.2	1009	1.27	2.50	0.658	1289
minimum :	3.0	1008	1.15	2.49	0.656	1163
average :	17.5	1008	1.21	2.50	0.657	1226
std.dev.:	6.2	0	0.03	0.00	0.000	26
c.v. (%):	36	0	2	0	0	2

Substituting the averaged values 1234 ($J.m^{-3}.K^{-1}$) for AUXIL instead of calculating it saves 6570 calculations (18 * 365). The effect of using a constant air heat capacity (AUXIL) would be mainly in the air dryness term, which proved to be not significant anyway.

Albedos (Albd)

Albedo denotes the ratio of (measured) incoming radiation over outgoing radiation. The values presented are based on measurements at 12.00 hours:

```
water       (AlbdWater) = 0.06
grass       (AlbdGrass) = 0.23
sunflower    (AlbdCrop) = 0.25
bare soil    (AlbdSoil) = 0.15
```

Aerodynamic resistances (R_a)

Aerodynamic resistance values ($s.m^{-1}$) were borrowed from literature. The formula used comes from the aerodynamic theory of turbulent flow, and can be approximated, according to Allen et al. (1989), by:

$$R_a = \frac{\{\ln[(Z_a - d) / Z_0]\} * \{\ln[(Z_t - d) / (0.1 * Z_0]\}}{(0.41)^2 * U_2} \qquad (4.37)$$

where R_a is aerodynamic resistance ($s.m^{-1}$).
Z_a is height of anemometer (m).
Z_t is height of thermometer and hygrometer (m).
Z_0 is "roughness", dependent on crop height (CH) (m).
d is zero plane displacement, dependent on crop height (m).
U_2 is wind speed at Z_a ($m.s^{-1}$).
0.41 is von Karman's constant.

For a relatively large expanse of dense agricultural crops Allen et al. (1989), suggest the following relations:

$$Z_o = 0.123 * CH \quad (4.38)$$
$$d = 0.67 * CH \quad (4.39)$$

where CH is crop height (m).

For an anemometer height of 2 m, thermometer and hygrometer heights of 1.5 m, and a crop height of 0.12 m (grass), the aerodynamic resistance can be estimated as follows:

$$R_a = 199 / U_2 \quad (4.40)$$

An alternative equation for crop roughness, suggested by Goudriaan, 1977,:

$$Z_o = 0.25 (CH - d) \quad (4.41)$$

leads to

$$R_a = 228 / U_2 \quad (4.42)$$

For a bare soil, the zero plane displacement is nil and the surface roughness is of the order of 3 mm. The aerodynamic resistance for bare soil is then:

$$R_a = 329 / U_2 \quad (4.43)$$

Normally, the crop height changes during the season. Table 4.14 shows the coefficients for a linear relation between LAI and CH for sunflower, based on data from two years (1993 and 1994).

Table 4.14.a. Coefficients for equation LAI = a + b * CH

Year	1993					1994			
Variety	A	B	C	avg	ALL	A	B	C	avg
a	-0.229	-0.179	-0.203	-0.202	-0.149	-0.039	-0.126	-0.128	-0.098
b	2.860	2.293	2.525	2.555	2.374	2.216	2.287	2.205	2.236
R Squared	0.999	0.999	0.998	0.999	0.995	0.943	0.993	0.983	0.978

Table 4.14.b. Coefficients for equation LAI = b * CH

Year	1993					1994			
Variety	A	B	C	avg	ALL	A	B	C	avg
b	2.610	2.102	2.334	2.346	2.223	2.180	2.157	2.087	2.141
R Squared	0.983	0.985	0.985	0.985	0.987	0.943	0.987	0.977	0.975

The coefficient of variance between varieties is 9 % and between years 7 %. Differences between years are partly caused by differences in weather conditions. Since, morphologically, all varieties are of the same stature, I suggest an approximate relationship for sunflower with a zero intercept:

$$LAI = 2.22 * CH \quad (4.44)$$

This relation holds for most of the growing season, but in the last part of the season LAI decreases without CH decreasing accordingly. LAI is calculated by the crop growth model. This value could still be used to estimate CH, if an extra condition is added to the program, viz that CH cannot decrease in value.

The suggested equation may be compared with the generic equation for field crops proposed by Allen et al. (1989):

$$LAI = 5.5 + 1.5 * \ln(CH) \quad (4.45)$$

Using equation (4.45), a crop with a crop height of 0.1 m would have already a LAI of 2.05. For sunflower it is suggested to use equation (4.44).

R_a can now be calculated as:

$$R_a = \frac{\ln\{2-0.67*CH)/(0.123*CH)\} * \ln\{1.5-0.67*CH)/(0.1*0.123*CH)\}}{(0.41)\hat{}2 * U_2} \quad (4.46)$$

The aerodynamic resistances used are:

```
RaWater = 30 s.m-1
RaSoil   : equation (4.43)
RaGrass  : equation (4.40)
RaCrop   : equation (4.46)
```

Crop resistances (R_c)

The crop resistances ($s.m^{-1}$) are calculated as suggested by Allen et al. (1989):

$$R_c = R_l / (0.5 * LAI) \quad (4.47)$$

where R_l is the stomatal resistance ($s.m^{-1}$), set to 100 $s.m^{-1}$ for the reference crop, and LAI is the leaf area index.

To compute the LAI of a reference crop Allen et al. (1989) suggest the following approximation:

$$LAI = 24 * CH \quad (4.48)$$

which brings the crop resistance of the reference crop to:

$$R_c = 100 / (0.5 * 24 * 0.12) = 70 \quad (4.49)$$

For sunflower, equation (4.47) can be used. The stomatal resistance of sunflower (R_l) is set to 200 ($s.m^{-1}$) in line with values reported in literature (CETIOM, 1992).

As LAI changes with the season, R_c changes as well. To avoid an infinite resistance value when LAI = 0, a maximum had to be set for R_c. A value of 1200 $s.m^{-1}$ was chosen, the same as the cuticular resistance, on the grounds that the maximum stomatal resistance is reached when all stomata are closed and resistance is entirely cuticular.

Consequently, the crop resistance for sunflower would be:

$$R_c = 200 / (0.5 * LAI) = 400 / LAI \qquad (4.50)$$

with a maximum of 1200 $s.m^{-1}$.

Crop resistances used are:
RcGrass = 70 $s.m^{-1}$ (equation 4.49).
RcCrop : equation (4.50).

Radiation and dryness terms

The contributions of radiation and air dryness to total evapotranspiration were calculated with data from Coria del Rio, 1992:

Table 4.15. ETO and its components 'radiation' and 'air dryness'.

Values	ETO	ETRad	ETDry
maximum :	5.9	5.0	2.3
minimum :	0.0	0.0	0.0
average :	2.4	1.8	0.6
std dev.:	1.7	1.4	0.4
c.v.(%) :	72	78	77
Total :	865	661	204

where ETRad is the contribution to ETO by radiation (RadTerm) and ETDry by air dryness (DryTerm). Data are in $mm.d^{-1}$.

The air dryness term accounts for 1/4 of total ET0. Consequently the simplification made by assigning a fixed value to the air heat capacity, 1234 $J.m^{-3}.K^{-1}$, instead of computing it, has no undesirable consequences. Fig. 4.22 shows the seasonal pattern of both terms of ET0 with weekly data.

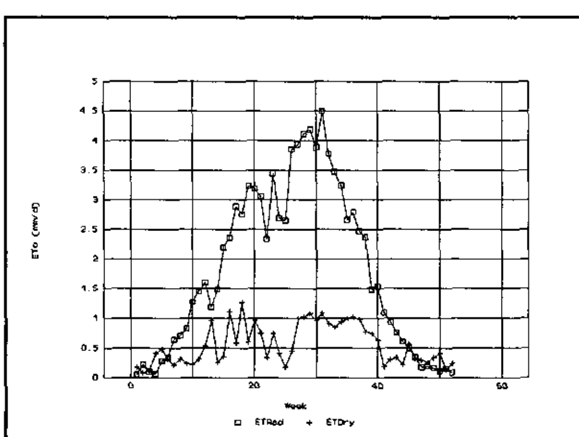


Fig. 4.22. Radiation (ETRad) and air dryness (ETDry) terms of ETO.

Calculations

Calculations of evapotranspiration are done using the program PENMAN.BAS (in Annex D). The calculations of energy income (shortwave, longwave, absorbed) are shared by the evapotranspiration module and the crop growth module.

The general Penman-Monteith equation can be applied for a water surface, a bare soil, a reference crop or an actual crop (E0, Esoil, ET0, ETcrop). The last two calculations can be used to assess the crop coefficient: Kc = ETcrop / ET0. As some of these calculations are still somewhat subjective, maximum Kc-value (from tables for a specific crop) were used to define the maximum value of ETcrop.

To run PENMAN.BAS independently of the crop model it is suggested:
1. to run first the program SUNFLOR.BAS for a PS1 scenario and output daily LAI-values
2. format LAI-values for input data to program PENMAN.BAS
3. read LAI(Day) and with it calculate:
   - crop height (CH using equation (4.44))
   - aerodynamic resistance (RaCrop using equation (4.46))
   - crop resistance (RcCrop using equation (4.50)).

4.3. **Data Base**

The input data required for land-use systems analysis can be grouped to four categories: weather data, soil data, crop data and management data. The management data define initial state variable values and permit the user to choose different scenarios; they are not pre-defined. All other input data are contained in files. In this way, every analysis considers daily weather data, a defined soil type and a specific crop, or crop variety.

The weather, soil and crop data needed for a particular analysis depend on the production situation under analysis. The variables considered and the file structure are discussed for each category of data. The files are listed in annexes: the crop file as SUNFLOR.DAT, the soil file as CDRSOIL.DAT (Annex D) and the weather files for Coria del Rio, 1993 and 1994, as CORIA93.DAT and CORIA94.DAT (Annex C).

Crop file

Required input data

Data needs for analysis of production situation:
PS1 : C3C4$, T0, TSUM, TLEAF, TLOW, SLAmax, SLAmin, Ke, r(org), EC(org), fr(org)
PS2 : (additional) RDSroot, RDm, RDint, PSIleaf, TCM
PS3 : (additional) NSO, NStraw, PSO, PStraw

These variables define:
Photosynthetic pathway: C3C4$

Temperature related characteristics: TSUM, TLOW, T0, TLEAF, RDSroot
Organ dm conversion factors: EC(org)
Organ dm partitioning: fr(org)
Organ maintenance costs: r(org)
Leaf development: SLAmax, SLAmin
Canopy characteristics: Ke
Management related characteristic: RDint
Soil and crop related characteristic: RDm
Water related characteristics: PSIleaf, TCM
Organ nutrient content: NSO, NSTRAW, PSO, PSTRAW

The structure of the crop file:
Croplabel$
C3C4$, T0, TSUM, TLEAF, TLOW, RDSroot, RDm, RDint, PSIleaf
SLAmax, SLAmin, Ke, TCM, RLeaf, RRoot, RStem, RSO
ECLeaf, ECRoot, ECStem, ECSO, NSO, NStraw, PSO, PStraw
NRpts
RDS(NRpts)
FRLeaf(NRpts)
FRRoot(NRpts)
FRStem(NRpts)
FRSO(NRpts)

Data definition

The various data come from literature review and field measurements. Field measurements are direct measurements or values may be compounded from several measurements.

The crop data required stem from the following sources:
Literature review: C3C4$, TLOW, TCM, r(org)
Field measurements: TSUM, T0, TLEAF, RDSroot, RDm, RDint, SLA, Ke, fr(org), RDm, RDint
Combination of both: PSIleaf, EC(org), NSO, NStraw, PSO, PStraw

Data obtained through literature review:

C3C4$: the photosynthetic pathway of sunflower is that of a C3 plant. This parameter is important for determination of the maximum rate of assimilation (AMAX).

TLOW: air temperatures of less than 0 degrees centigrade are harmful to sunflower. It is assumed that one day of frost kills a sunflower crop.

TCM: the mid-season crop coefficient is around 1.2. This value represents the ratio of the maximum over the potential evapotranspiration rate.

r(org): organ-specific relative maintenance respiration rates are set to 0.05, 0.01, 0.0075 and 0.023 for leaf, root, stem and storage organ respectively. The values for root, stem and storage organ are quite stable. Room is left to adjust the value of r(leaf) as it depends greatly on the composition of the leaf tissue. For sunflower, it must be assumed that some of the costs of maintenance are borne by assimilation by the storage organ (the head's back side).

Data obtained from field measurement(s):

TSUM: this parameter refers to the heat requirement of the crop for full development, from emergence till physiological maturity. It is defined as the cumulative sum of daily effective temperatures, i.e. of the difference between the daily average temperature (T24h) and the threshold temperature for development (T0). Examples of TSUM data obtained in the two seasons:

Table 4.16. Heat requirement.

Year	Duration in days	Average daily temperature over the crop cycle (°C)
1993	107	20.0
1994	101	20.8

The average development rate is 0.000694 (which brings the value of TSUM to 1440 °C.d); the base temperature (T0) amounts to 6.5 °C. These values are indicative because the canopy temperature may be different from the air temperature.

T0: the threshold temperature for development may vary with the physiological stage, viz germination, vegetative or reproductive phases. Data from literature suggest that development of sunflower does not take place at temperatures below 6 °C, what agrees with the previous calculation.

TLEAF: the heat requirement for full leaf development (°C.d) defines the leaf lifespan. Measurements of dead leaf mass over time suggest a value of some 900 °C.d.

Ke: the extinction coefficient for visible light was calculated using the equation: I = Ia * EXP (-LAI * Ke); the incoming radiation above the canopy (Ia) and under the canopy (I), and the LAI are measured. The calculated value is 0.9 which conforms with literature data.

fr(org): the partitioning fractions of assimilates to various plant organs are described in chapter 4.2 (dry matter partitioning).

The suggested FIXED values are shown in Table 4.17:

Table 4.17. RDS-to-fr(org) relations for sunflower.

RDS	Root	Stem	Leaf	S.O.
0.00	0.20	0.19	0.61	0.00
0.11	0.18	0.19	0.63	0.00
0.19	0.17	0.21	0.62	0.00
0.35	0.15	0.31	0.53	0.01
0.55	0.12	0.31	0.35	0.23
0.80	0.00	0.00	0.13	0.87
1.00	0.00	0.00	0.00	1.00

Fractioning as a function of dry matter ratios was described by the following set of equations:

Storage organ/Leaf-ratio (soLf):

```
soLf = -1.4 + 3.5 * RDS                                          (4.51)
  if RDS < 0.40 then soLf = 0
```

Stem/Leaf-ratio (StLf):

```
StLf = 2 * RDS                                                   (4.52)

If StLf > 1.1 then StLf = 1.1
```

The Root/Leaf-ratio (RootLeaf) is constant at 0.35.

Root variables: **RDint**, **RDm** and **RDSroot**
Plant roots occupy a nominal soil volume that is a function of the momentary depth of a uniform rooting zone. The equivalent rooting depth depends on the pattern of root distribution. For sunflower, this pattern is conical; integration over depth yields an equivalent root volume that extends down to a depth 0.5 * RDm.

Actual rooting depth increases over time, from an initial value **(RDint)** to a maximum value **(RDm)**. RDint is set at the depth of sowing plus the root length at emergence. **RDm** is reached at the point when relative development reaches the value RDSroot and allocation of assimilates for the growth of the root system stops. Average root length (33 cm) and maximum rooting depth (100 cm) were measured. Maximum rooting depth represents the depth that the deepest roots can reach.

Root length measurements suggest a linear increase in rooting depth between RDint and RDm.

Under water stress, the real rooting depth may increase but the equivalent rooting depth is assumed to remain the same.

The value of **RDSroot**, the relative development stage at which root growth ceases, can be inferred from two sets of data: 1) the relative development stage at which root length reaches its maximum value, and 2) the relative development stage at which no more assimilates are allocated to the roots.
This point matches then with the point at which fr(root) is null.

The available data suggests the following values on root characteristics:

```
RDint    =  10 cm
RDm      = 100 cm
RDSroot = 0.70
Root growth rate  = linear
Root distribution = conical
```

The momentary equivalent rooting depth is described by:

```
if RDS  = < RDSroot then
     RD = RDint + (0.5 * RDm - RDint) * RDS / RDSroot            (4.53a)
else RD = 0.5 * RDm                                              (4.53b)
```

```
where
RDS      is relative development stage (-).
RDSroot is relative development stage at which root growth ceases (-).
RD       is momentary equivalent rooting depth (cm).
RDint    is equivalent rooting depth at emergence (cm).
RDm      is maximum rooting depth (cm).
0.5     is integration factor depending on the root distribution pattern.
```

Measured root lengths are shown in Fig. 4.23:

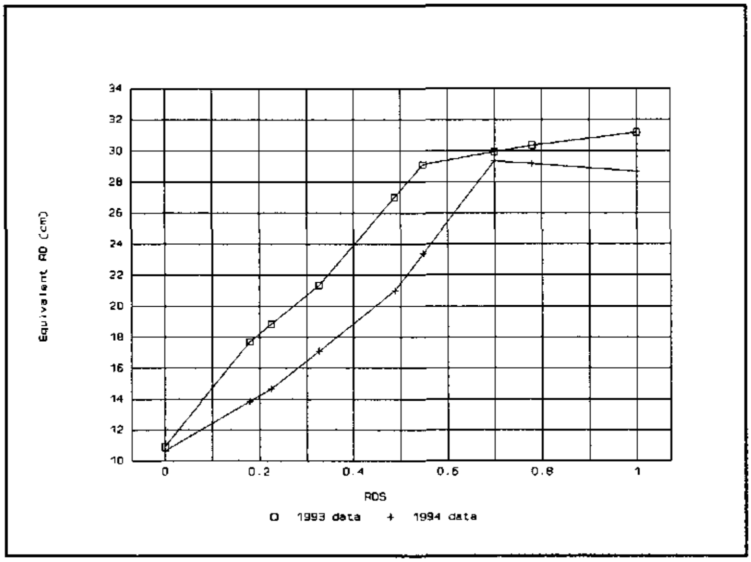


Fig. 4.23. Equivalent rooting depth.

SLA: the specific leaf area ($m^2.kg^{-1}$) represents the total leaf area per unit dry leaf mass; the SLA value varies with the relative development stage and growing conditions.

Sunflower forms thicker leaves as it develops so that the value of SLA decreases from a maximum value, early in the season, **(SLAmax)**, to a minimum value at the end, **(SLAmin)**. This is described by the equation:

```
SLA = SLAmin - (SLAmax - SLAmin) * Ln(RDS)                    (4.54)
```

The logarithmic curve is truncated until shortly after the beginning of the season, so that SLAmax is not exceeded:

```
if SLA > SLAmax then SLA = SLAmax                             (4.55)
```

Thickening of the leaves, i.e. the decrease of SLA, depends also on the availability of water, which is described by the CFWATER parameter. Measured SLA data for the three treatments (W (Wet), H (Half) and D (Dry)) are shown in Fig. 4.24.

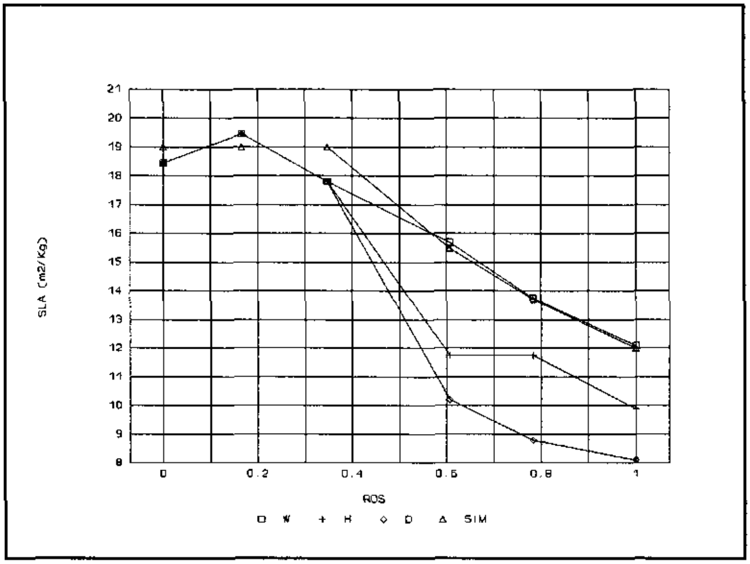


Fig. 4.24. SLA as a function of the relative development stage of the crop. where W stands for 'Wet', H for 'Half', D for 'Dry' and SIM for 'Simulation'.

At emergence, the plant has only one pair of true leaves, these expand until a maximum SLA value is reached: the leaves are thinnest. This point is reached very early in crop development, roughly when phyllothaxy changes.

The SIM curve in Fig. 4.24 shows similarity with equations (4.54) and (4.55). Data fitting produced an R^2 value of 0.96, despite the truncation. Table 4.18 summarizes the data of Fig. 4.24 along with the fitting of the other two curves.

Table 4.18. Measured SLA data for three treatments and simulated values of SLA and coefficients of water availability.

	SLA data			Simulation				
RDS	Aw	Ah	Ad	Aw	cf(W)	Ah	cf(W)	Ad
0.00	18.5	18.5	18.5	19.0	1.00	19.0	1.00	19.0
0.17	19.5	19.5	19.5	19.0	1.00	19.0	1.00	19.0
0.35	17.8	17.8	17.8	19.0	1.00	19.0	1.00	19.0
0.61	15.7	11.8	10.2	15.5	0.76	11.8	0.66	10.2
0.78	13.8	11.8	8.8	13.7	0.85	11.7	0.64	8.8
1.00	12.1	9.9	8.1	12.0	0.82	9.8	0.67	8.0

where cf(W) is the correction factor for availability of water, CFWATER.

The simulated values were obtained by multiplying calculated constraint-free SLA values by the coefficient of water availability:

SLAsim = SLA * CFWATER (4.56)

where
SLA is SLA calculated with equation (4.54).
SLAmax = 19 ($m^2.kg^{-1}$).
SLAmin = 12 ($m^2.kg^{-1}$).

Although appealing, equation (4.56) cannot be used on a daily basis, but only as an weighted value for a certain period of time (otherwise imagine a day with CFWATER = 0 !).

A more elegant alternative that avoids these calculations is to account for the effect of dryness on the length of crop growth,by considering the canopy temperature: a same TSUM value could be used and crop growth would be faster.

Differences between varieties will be discussed in section 4.4 (model calibration and sensitivity testing).

Data obtained from literature and field measurements:

PSIleaf: the 'critical leaf water head' represents the maximum suction, in hPa, that a plant can build up to extract moisture from soil. PSIleaf must be known to compute the maximum rate of water uptake:

```
MUR = (PSIleaf - PSI) / (Rplant + Rroot)                              (4.57)

where
PSIleaf is critical leaf water head (hPa).
PSI     is soil moisture potential (hPa).
Rplant  is resistance over the distance of moisture flow through the plant
        (hPa).
Rroot   is resistance over the distance of flow to the root system (hPa).
```

Flow through the plant is driven by the difference in potential between the rooted soil (defined by the soil matric suction, PSI) and the critical leaf water potential (PSIleaf). PSIleaf is a crop characteristic.

Indicative values for the flow resistance terms are obtained with:

```
Rplant = 680 + 0.53 * PSIleaf  (d)                                    (4.58)
Rroot  = 13 / RD * KPSI        (d)                                    (4.59)
```

The above equations are empirical and can at best give approximate values for Rplant and Rroot.

MUR is nil when PSI becomes equal to PSIleaf; no water can be extracted any more and the plant wilts. The PSI value at which this happens does not depend on the soil (as wrongly assumed in the permanent wilting point' definition of pF 4.2, which is fully a soil parameter) but on the value of PSIleaf.

At full supply of water, the value of PSI becomes negligible relative to the value of PSIleaf, and the value of Rroot becomes negligible relative to Rplant. MUR is then identical to the theoretical maximum transpiration rate of a closed sunflower crop (MTR):

```
MTR = PSIleaf / Rplant                                                (4.60)
```

For an indicative value of PSIleaf of 14000, the value of Rplant would be 8100 and the theoretical maximum MTR value would be 1.73 ($cm.d^{-1}$).

The following table is constructed for a set of PSI values, from PSIleaf down to 1 hPa, using the listed equations and the relations:

```
if PSI<PSImax then KPSI = K0 * exp(-ALFA * PSI)          (4.61a)
               else KPSI = AK * PSI ^ -n                  (4.61b)
SMPSI = SM0 * PSI ^ (- GAM * ln(PSI))                     (4.62)
```

with the following parameters:

```
PSIleaf = 14000          n =  2.1
 Rplant =  8100         K0 = 24
     RD =    30       ALFA =  0.038
     AK =     1.5      SM0 =  0.5
 PSImax =   305        GAM =  0.018
```

Table 4.19. MUR sample calculations.

pF	PSI	SMPSI	KPSI	log KPSI	Rroot	MUR
4.1	14000	0.10	0.000000	-8.5	1.47E+08	0.00
4.0	11000	0.11	0.000000	-8.3	8.86E+07	0.00
3.5	3500	0.15	0.000000	-7.3	8.00E+06	0.00
3.2	1500	0.19	0.000000	-6.5	1.35E+06	0.01
3.0	1000	0.21	0.000000	-6.1	5.76E+05	0.02
2.9	800	0.22	0.000001	-5.9	3.61E+05	0.04
2.7	500	0.25	0.000003	-5.5	1.34E+05	0.09
2.5	350	0.27	0.000006	-5.2	6.36E+04	0.19
2.2	150	0.32	0.080303	-1.1	5.40E+00	1.71
2.0	100	0.34	0.536898	-0.3	8.07E-01	1.72
1.7	50	0.38	3.589646	0.6	1.21E-01	1.72
0.0	1	0.50	23.10511	1.4	1.88E-02	1.73

Plotting MUR against pF yields:

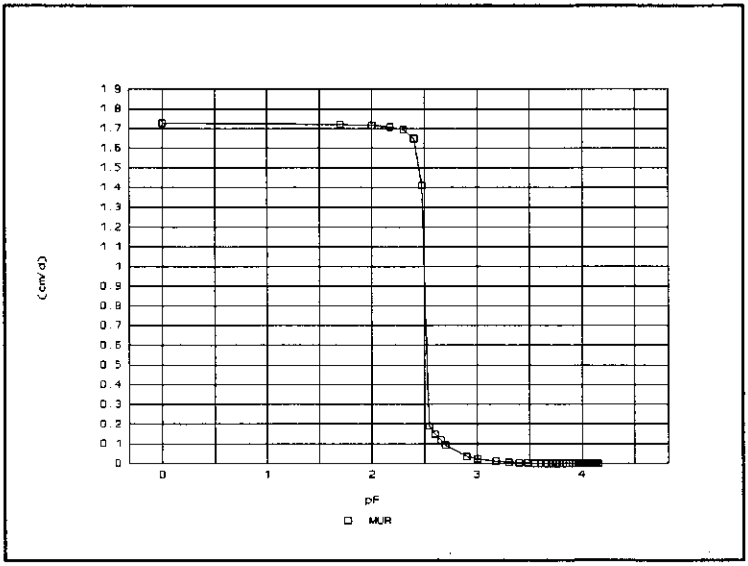


Fig. 4.25. MUR-to-pF relation.

The dry bulk density of the studied soil is 1.34 $g.cm^{-3}$ (with a coefficient of variance of 6 %). The average volumetric water contents at a soil moisture content of PSIleaf hPa are listed in Table 4.20:

Table 4.20. Soil moisture content ($cm^3.cm^{-3}$) at permanent wilting point.

Var	average	maximum	minimum
A	9.5	10.1	8.9
B	9.4	9.9	9.0
C	9.6	10.2	9.3

These Θ-values are associated with coefficients of variance ranging from 6 to 2 %. The absolute maximum values obtained for the three varieties are: 14.5, 14.7 and 13.7 respectively.

PSIleaf values can now be obtained by plotting these Θ-values on the corresponding pF curve as shown in the Fig. 4.25. The sample curve suggests PSIleaf suctions between 36000 and 160000 hPa. If the maximum observed Θ-values were used instead of averaged values, the PSIleaf suctions would range between 14500 and 22000 respectively. Inaccuracies in the determination of bulk density, Θ-value and pF curve obscure any difference between varieties. It appears that the indicative nature of the pF-curve, particularly in the high suction range where small errors in (logarithmic) moisture retention entail considerable differences in PSI-values, preclude accurate determination of PSIleaf with this approach. The default value of 14000 hPa will therefore be used henceforth.

EC(org): To convert the sugars synthesized in assimilation to structural plant matter, the efficiency of conversion must be known. This efficiency depends on the composition of the plant material and varies considerably between plant organs.

Penning de Vries (quoted by Lövenstein et al., 1992) suggests the following chemical composition and conversion factors (CF):

Leaves (in general):

```
composition       biosynthesis costs
52 % carbohydrates --- 1.275  )
25 % proteins -------- 1.920  )
 5 % fat ------------- 3.189  ) ==> 1.47 g glucose / g leaf
 5 % lignin ---------- 2.231  )
 5 % organic acids --- 0.954  ) CF = 1/1.47 = 0.68 g leaf / g glucose
 8 % minerals -------- 0.120  )
```

where 1.47 is the sum of multiplying composition by biosynthesis costs.

Average CF values for other organs:

```
leaf   0.68
stem   0.66
root   0.68
```

On the basis of these values, the generic CF value for leaf, stem and root mass is set to 0.7.

Sunflower heads (including the seeds) have the following composition:

```
45 % carbohydrates
14 % proteins
22 % fat
13 % lignin
 3 % organic acids
 3 % minerals
```

If the same biosynthesis costs are used as in the calculation of CF(leaves), the conversion efficiency amounts to 1 / 1.86638 = 0.54.

Seed analysis produced the following average values:

```
Water      5 %
Oil       44 %
DDM       51 %
  of which: Fibre      23 %  or (12 %) of total
            Protein    33 %     (17 %)
            Rest       44 %     (22 %)
 (DDM is defatted dry matter).
```

Calculating the conversion efficiency for sunflower seeds yields:

```
        composition  biosynthesis costs
fat         0.46      *    3.189          = 1.47   )
lignin      0.13      *    2.231          = 0.29   )
protein     0.18      *    1.920          = 0.35   ) ==>1 / 2.39 = 0.42
rest        0.23      *    1.275          = 0.29   )
                          (0.120)                            (==> 0.47)
```

In brackets the extreme value that the fraction "rest" could have.

The measured ratio of seed dry matter to full s.o. mass was 0.70. This ratio can be used to calculate a CF value for the entire s.o.:

```
a) CF seed = 0.42         CF s.o. =  0.70 * 0.42 + 0.30 * 0.66 = 0.49
b) CF seed = 0.47         CF s.o. =  0.70 * 0.47 + 0.30 * 0.66 = 0.53

   with CF s.o. heads = CF stem = 0.66
```

This reasoning suggests that CF s.o. could lie between 0.49 and 0.53; close to the value of 0.54 proposed by Penning de Vries.

On the basis of the foregoing calculations, the following indicative conversion efficiency values are suggested:

EC(leaf)	EC(root)	EC(stem)	EC(s.o.)
0.68	0.68	0.66	0.54

N and P contents of plant material: NSO, NStraw, PSO, PStraw

Minimum concentrations of nutrient elements in plant tissue differ significantly between storage organ and 'straw'.

The following indicative minimum concentrations of N, P and K in storage organ and straw of oil seed crops are suggested by van Keulen and Wolf (1986):

	N	P	K	P/N	P/K
Seed	0.0155	0.0045	0.0055	0.29	0.82
Straw	0.0034	0.0007	0.0080	0.25	0.09

P/N ratios in plant tissue range in practice from 0.04 to 0.15. Measured data from Carter (1978) are, by and large, slightly above the minimum values, and P/N ratios are within the range suggested:

	N	P	K	P/N	P/K
Seed	0.0240	0.0035	0.0055	0.15	0.64
Straw	0.0056	0.0010	0.0081	0.17	0.12

The concentrations of nutrient elements in plant organs vary over the growing season. Field data suggest the following values for physiologically mature sunflower:

Organ	N	P	K	P/N	P/K
Leaf	0.0139	0.0017	0.0580	0.12	0.03
Stem	0.0074	0.0011	0.0756	0.15	0.01
Root	0.0041	0.0008	0.0179	0.19	0.04
s.o.	0.0336	0.0042	0.0105	0.13	0.40

Using the dry matter distribution at harvest (still indicative):

```
Root = 0.07
Stem = 0.24
Leaf = 0.23
s.o. = 0.46 (with Seed / s.o. = 0.70)
```

leads to:

Organ	N	P	K	P/N	P/K
s.o.	0.0154	0.0019	0.0048	0.13	0.40
straw	0.0053	0.0007	0.0328	0.14	0.02

The suggested input values for the sunflower crop data file are then:

```
NSO       0.0154
NStraw    0.0053
PSO       0.0019
PStraw    0.0007
```

Soil file

Required input data

Soil/land data are only required for production situations 2 and 3:
PS2/3 : SM0, GAM, PSImax, K0, ALFA, AK, S0, Ktr

management:
PS2/3: PSint, ASSC, SSint, ZTint, FIXZT$, Irrigation timing & depth

These variables define:
Moisture retention curve: GAM
Hydraulic conductivity curve: K0, ALFA, AK, PSImax
Infiltration characteristics: S0, Ktr
Soil porosity: SM0

The structure of the soil file:
Soillabel$
SM0, GAM
PSImax, K0, ALFA, AK
S0, Ktr

Data definition

All soil/land data are obtained from field and laboratory measurements.

Texture:
Determining the percentages of clay, silt and sand at different sites and depths reveals that the soil materials of the study area belong to three textural classes: loam, clay loam and sandy clay loam. The rooted soil compartment has a loamy texture (44 % sand, 25 % clay and 31 % silt).

Bulk density ($g.cm^{-3}$):
The dry bulk density (φ) is used to convert gravimetric water content (w) into volumetric water content (Θ):

$$\theta = w * \varphi \quad (4.63)$$

Bulk density measurements were done for several applications. Averaging all data available produces a value of 1.34 $g.cm^{-3}$.

Total soil porosity (**SM0**, in $cm^3.cm^{-3}$) can be calculated with:

$$SM0 = 1 - \varphi / \varphi_S \quad (4.64)$$

The measured specific density of the solid phase (φ_S) of 2.6 $g.cm^{-3}$ and a porosity of 0.50 $cm^3.cm^{-3}$ (SM0), conform with a φ value of 1.3 $g.cm^{-3}$.

Small cracks develop at the end of the growing season when the soil is dry. In addition, bulk density values vary as a consequence of soil tillage and soil compactation.

pF values:
The moisture retention characteristics of the soil are shown in Table 4.21, that presents measured soil moisture (Obs.) data and simulated values (Calc1 and Calc2). The following moisture retention function is used:

$$SMPSI = SM0 * PSI \wedge {}^{(-GAM * \ln(PSI))} \quad (4.65)$$

where
SMPSI is volume fraction of moisture in soil with suction PSI ($cm^3.cm^{-3}$).
SM0 is total pore fraction ($cm^3.cm^{-3}$).
PSI is matric suction of rooted soil (cm).
GAM is texture-specific constant (cm^{-2}).

Table 4.21. pF data, corresponding PSI (in hPa) and measured (Obs.) and simulated SMPSI (Calc1 and Calc2).

		SMPSI		
pF	PSI	Obs.	Calc1	Calc2
0	1	0.48	0.48	0.50
0.5	3	0.47	0.47	0.49
1.0	10	0.45	0.44	0.45
1.2	16	0.44	0.42	0.43
1.5	32	0.42	0.39	0.40
2.5	316	0.27	0.27	0.27
4.2	15849	0.08	0.09	0.09
7.0	10000000	0.00	0.00	0.00

where Calc1 is based on optimized parameters SM0 and GAM.
In Calc2, SM0 is fixed and GAM optimized.

The parameter values are optimized for equation (4.65) to fit the measured values. For Calc1, the value of SM0 was a calculated 0.497 $cm^3.cm^{-3}$ and GAM was 0.018124 cm^{-2} with an R^2 of 0.995. For Calc2, SM0 was rounded to 0.50 $cm^3.cm^{-3}$ and GAM calculated as 0.018378 cm^{-2}, again with an R^2 of 0.995. This suggests that the GAM value can be rounded without losing accuracy, so the final values are SM0 = 0.50 $cm^3.cm^{-3}$ and GAM = 0.018 cm^{-2}.

The pF curve, measured and calculated, is shown in the next graph:

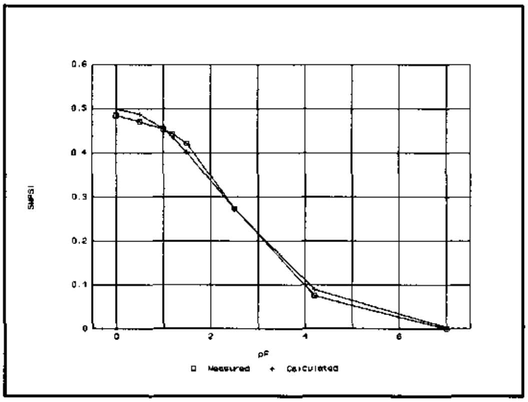


Fig. 4.26. pF curve.

KPSI-PSI curve:
Hydraulic conductivity measurements were done using the multi-step outflow method, i.e. by applying pressures (from low to high) to an aliquot of wet soil in a pressure cell. Moisture loss from the sample was plotted against time. The SFIT model (Kool and Parker, 1987) was used to generate the KPSI-PSI curve. The unsaturated hydraulic conductivity (K) is calculated with the following equations (Parker et al., 1985):

$$Se = (1 + |LAMBDA * h|^{n})^{-m} \tag{4.66}$$

$$K = K0 * Se^{KAPA} * (1 - (1 - Se^{1/m})^{m})^{2} \tag{4.67}$$

where
Se is relative saturation (-).
LAMBDA is reciprocal value of the air entry suction (cm^{-1}).
h is pressure head (cm).
n, m are empirical parameters (-).
K0 is saturated hydraulic conductivity ($cm.d^{-1}$).
KAPA is fitting parameter (-).

The results of the measurements are shown in the next graph.

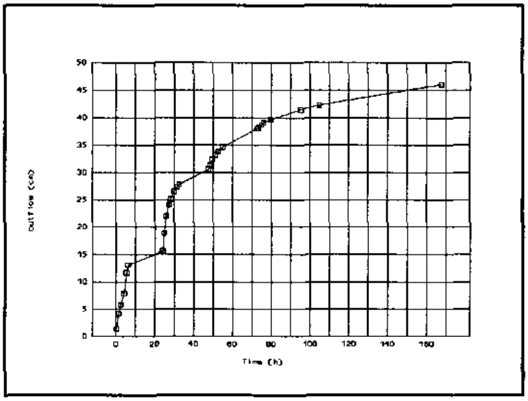


Fig. 4.27. Outflow measurements.

The pressures used (in cm) were 50, 150, 500 and 1000 respectively; they were applied after the following intervals had passed: 0, 24, 47.75 and 72.42 hours.

The SFIT model was run with the following parameter values:

SMO = 0.50 (total pore fraction, $cm^3.cm^{-3}$).
SMR = 0.09 (residual moisture content, $cm^3.cm^{-3}$).
KO = 1 (saturated hydraulic conductivity, $cm.h^{-1}$).
φ = 1.34 (dry bulk density, $g.cm^{-3}$).

which produced the sets of optimized parameter values presented in Table 4.22, for use in equations (4.66) and (4.67):

Table 4.22. Optimized parameter values.

Sample	Set	Fit	LAMBDA	n	m	KO	KAPA	R^2
* 7	2	7	0.0719	1.2361	0.1910	1	-0.6111	0.96
	3	11	0.0832	1.2208	0.1809	1	-0.9627	0.97
	4	3	0.0369	1.2683	0.2115	1	0.5000	0.96
* 8	5	6	0.0146	1.2341	0.1897	1	0.5000	0.91
	6	5	0.0247	1.1870	0.1575	1	-1.1723	0.91
	7	4	0.0135	1.2403	0.1937	1	0.5000	0.91
* 9	8	6	0.0441	1.1503	0.1307	1	0.5000	0.93
	9	5	0.0488	1.1621	0.1395	1	0.5000	0.90
	10	6	0.0262	1.1605	0.1383	1	0.5000	0.91
* 10	11	10	0.0303	1.2263	0.1845	1	0.5000	0.94
	12	10	0.0326	1.2166	0.1780	1	0.3829	0.94
	13	10	0.0198	1.2524	0.2015	1	0.5000	0.92

Relative saturation (Se) is equal to the soil moisture content divided by the total pore fraction. Table 4.23 is constructed by calculating Se (with equation 4.67) for the optimized parameters (in Table 4.22, sets 2 to 13) and multiplying the result by SM0. SMPSI is calculated with equation 4.66 (SMPSI = SM0 * PSI ^ (- GAM * Ln(PSI)).

Table 4.23. SMPSI and Se*SMO values with optimized parameters.

pF	SMPSI	Se*SMO											
		2	3	4	5	6	7	8	9	10	11	12	13
0	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1	0.45	0.45	0.45	0.47	0.49	0.49	0.49	0.48	0.48	0.49	0.48	0.48	0.49
2	0.34	0.31	0.31	0.34	0.42	0.40	0.42	0.39	0.38	0.41	0.37	0.37	0.39
3	0.21	0.18	0.19	0.19	0.27	0.27	0.27	0.28	0.27	0.30	0.23	0.23	0.23
4	0.11	0.11	0.11	0.10	0.16	0.18	0.15	0.20	0.18	0.20	0.14	0.14	0.13
4.2	0.09	0.09	0.10	0.09	0.14	0.16	0.14	0.19	0.17	0.19	0.12	0.13	0.12
5	0.05	0.06	0.07	0.06	0.09	0.12	0.09	0.14	0.13	0.14	0.08	0.09	0.07
6	0.02	0.04	0.04	0.03	0.05	0.08	0.05	0.10	0.09	0.10	0.05	0.05	0.04
7	0.00	0.02	0.02	0.02	0.03	0.05	0.03	0.07	0.06	0.07	0.03	0.03	0.02

Fig. 4.28 presents SMPSI and the different Se*SM0 sets. Only those Se*SM0 curves are shown which define extreme ranges; the others fall in between.

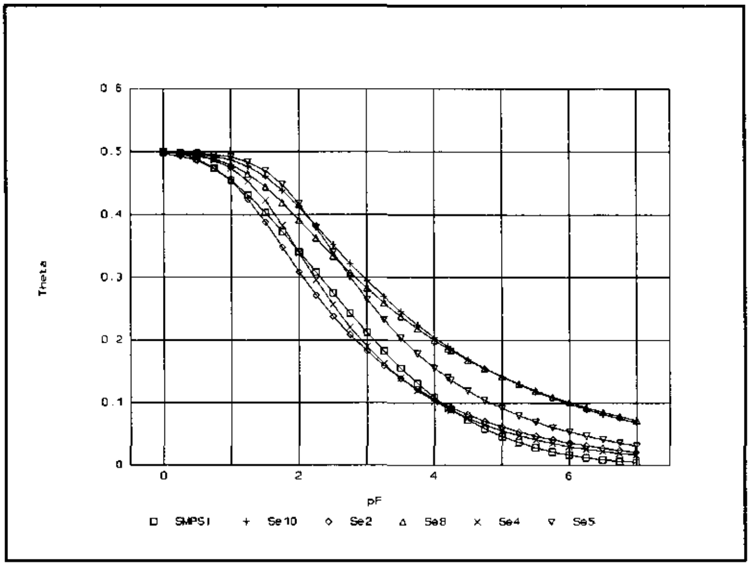


Fig. 4.28. Se*SMO curves. The number after Se represents the set number in Table 4.22.

The SMPSI curve lies always close to the lower range of the Se*SM0 curves.

A linear regression was made between each of the Se*SM0 curves (Table 4.23) and SMPSI. The result is shown in Table 4.24.

Table 4.24. Linear regression of SMPSI and Se*SM0 curves.

Set	Constant	X Coef.	R^2
2	0.009	0.939	0.99
3	0.016	0.919	0.99
4	0.003	0.998	0.99
5	0.045	0.993	0.99
6	0.070	0.921	0.99
7	0.043	1.001	0.99
8	0.096	0.844	0.99
9	0.079	0.867	1.00
10	0.097	0.869	0.99
11	0.032	0.971	1.00
12	0.038	0.958	1.00
13	0.025	1.009	0.99

In spite of the differences between the Se*SM0 curves shown in Fig. 4.28, they are strongly correlated with the SMPSI curve.

Fig. 4.29 shows KPSI-pF curves (calculated with equation 4.67). Here, as in the previous figure, only the extreme ranges are shown.

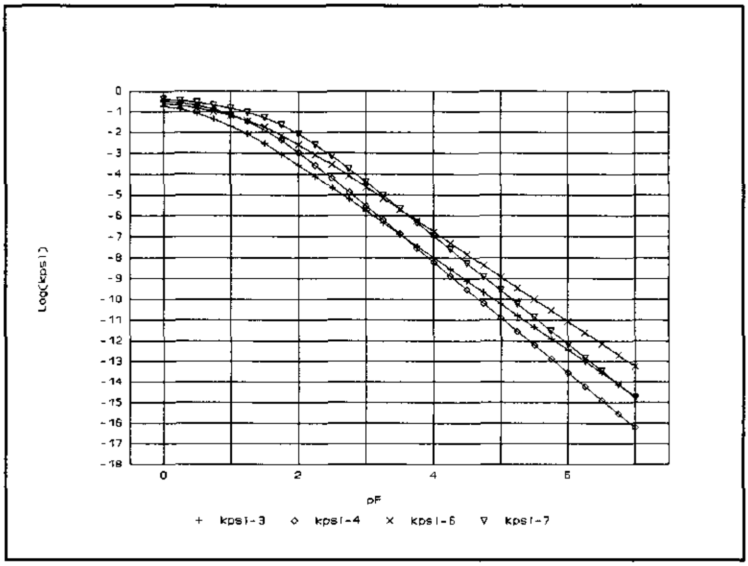


Fig. 4.29. KPSI curves. The figure after KPSI indicates the corresponding Se set.

The KPSI to PSI relation is described by two equations. At low suction it reads:

$$KPSI = K0 * EXP\ (-\ ALFA * PSI) \qquad (4.68a)$$

and at high suction:

$$KPSI = AK * PSI^{-n} \qquad (4.68b)$$

The divide between the low suction and the high suction ranges is at PSImax hPa; where equation (4.68a) equals equation (4.68b). Parameters ALFA, AK and n were obtained by curve fitting. Matching the data obtained by the SFIT model with equations (4.68a) and (4.68b) produced the following parameter values:

K0	=	1	(saturated hydraulic conductivity, cm h^{-1}).
ALFA	=	0.038	(texture-specific geometry constant, cm^{-1}).
AK	=	1.5	(texture-specific empirical constant, $cm^{-2.4}.h^{-1}$).
n	=	2.1	(empirical constant, -).
PSImax	=	305	(texture-specific suction boundary, cm).

Comparison of inferred (from Se) and calculated KPSI-values yields the values plotted in Fig. 4.30.

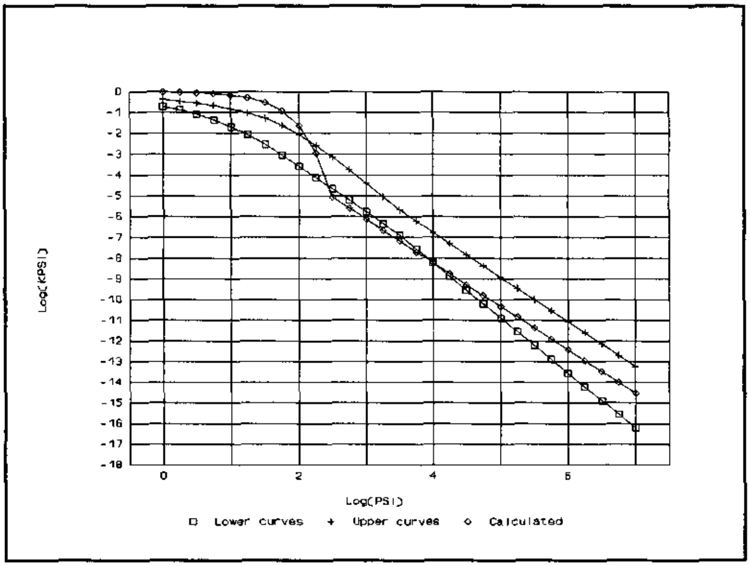


Fig. 4.30. KPSI to Log(PSI) curve.

In Fig. 4.30 the curve "Lower curves" is taken from the lowest value of curves KPSI-3 and KPSI-4, and "Upper curves" is taken from the highest value of curves KPSI-6 and KPSI-7 of Fig. 4.29.

Maximum rate of infiltration (IM):
Fig. 4.31 shows measured (referred as 'Data') and simulated (SIM) cumulative infiltration.

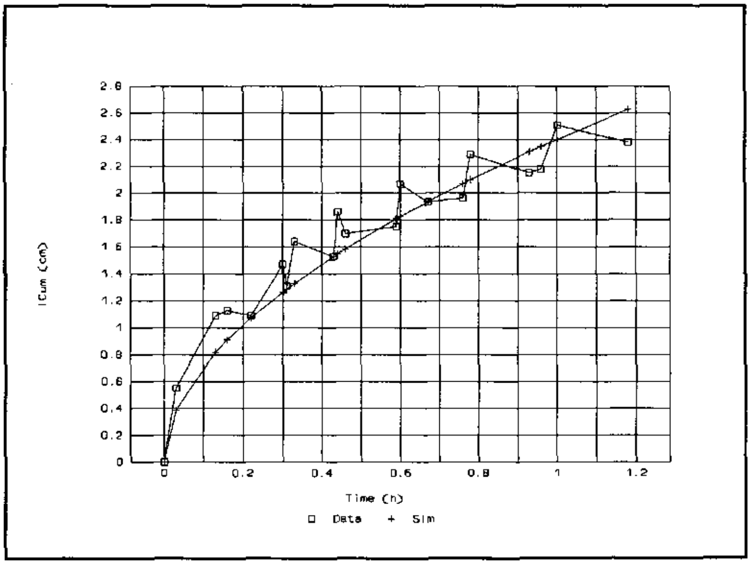


Fig. 4.31. Measured and simulated infiltration curves.

The simulation curve follows the equation:

```
ICum = A0 * SQRT(t) + A1 * t                                    (4.69)

where
ICum      is cumulative infiltration (cm).
t         is time (h).
A0 and A1 are fitting parameters.
```

The results are: A0 = 2.2, A1 = 0.2, R^2 = 0.94.

The infiltration rate at a time (t) is then the derivative of equation (4.69):

```
i = dICum / dt = A0 / (2 * SQRT(t)) + A1                        (4.70)
```

In the water balance model, infiltration is described with the following equations:

```
IM = 0.5 * SPSI * Dt^-0.5 + Ktr                                 (4.71)

with  SPSI = S0 * (1 - SMPSI/SM0)                               (4.72)

where
IM   is maximum rate of infiltration (cm.d-1).
SPSI is actual sorptivity (cm.d-0.5).
Dt   is time interval (d).
Ktr  is hydraulic permeability of transmission zone (cm.d-1).
S0   is reference sorptivity (cm.d-0.5).
```

Equations (4.70) and (4.71) suggests that A0 = SPSI and A1 = Ktr. For a completely dry soil, SPSI = S0; and for a completely wet soil SPSI = 0.

Equation (4.71) has a time interval of 1 day, where equation (4.69) is hourly. To convert the values of the fitting parameters for daily interval, A0 has to be multiplied by the square root of 24; and A1 by 24. In the soil data file, variable S0 is assigned the value of 10.78 ($cm.d^{-0.5}$), and Ktr the value of 4.8 ($cm.d^{-1}$).

Weather file

<u>Required input data</u>

Weather data needs for the various production situations:
PS1: Location, Tmax, Tmin, SunH, RHA
PS2 added data: PREC, E0, ET0 (or PREC, Wind speed to compute E0 and ET0)

All data are daily weather data over at least the crop growth period. The data refer to one geo-referenced site (latitude, longitude, altitude). E0 and ET0 are either input or have to be calculated/estimated.

These data entries define:
the location of the site: latitude, longitude, altitude
the temperature regime: Tmax, Tmin
the water budget: PREC, E0, ET0, RHA, (Wind speed)

the radiation income: SunH

The structure of the weather file:
line 1: Sitelabel, latitude, longitude, altitude
line 2 to 336: Day, Tmax, Tmin, PREC, RHA, SunH, Wind speed (for calculation of E0 and ET0)

Data definition

All weather data come from a weather station at some 100 meters distance from the experiment fields. All data were recorded with standard meteorological equipment:
Tmax: maximum temperature (°C).
Tmin: minimum temperature (°C).
PREC: precipitation ($mm.d^{-1}$).
RHA: relative humidity of air (-).
SunH: daily sun hours ($h.d^{-1}$).
Wind: wind speed ($m.s^{-1}$).

Calculated weather variables

The calculation of derived variables was described in chapter 4.2.

DL : day length ($h.d^{-1}$) is calculated as a function of the latitude and the day in the year.
EXTRA: extraterrestrial radiation ($MJ.m^{-2}.d^{-1}$) is estimated from the latitude and the day in the year.

TRANS: atmospheric transmissivity (-), is estimated as a function of latitude, DL, SunH and RHA.

E0, ET0 and **ETc** : reference and crop evapo(transpi)ration rates ($mm.d^{-1}$), are estimated with the Penman-Monteith approach.

Daily course of temperature : daytime **(Tday)**, nighttime **(Tnigth)** and equivalent daily temperature **(T24h)** are estimated by fitting of a coupled curve, sinusoidal at daytime and exponential at night.

Internal data consistency

Data screening for missing or corrupt weather data was done to check data consistency, data correlations and/or limits of data values, particularly for day length and daily sunshine hours (DL and SunH), global and extraterrestrial radiation (Rad and EXTRA), global radiation and daily sunshine hours (Rad and SunH), daily temperature fluctuations and atmospheric transmissivity (Ampl and TRANS), and humidity and precipitation (RHA and PREC).

Characterization of the site

Generalized weather data for Coria del Rio (averaged for 1993 and 1994) are shown in Table 4.25. This table and the original daily data show some remarkable features:

a. Temperature:
   Extreme temperatures (max, min, ampl): 43.5, -2, 27.0 °C.
   Averages temperatures (max, min, avg, ampl): 25.1, 11.7, 18.4, 13.4 °C.
   Number of days with low temperatures (< = 0 °C): 5
   First day with maximum temperature higher than 30 °C: 27 April
   First day with maximum temperature higher than 35 °C: 5 June

b. Radiation
   Maximum possible sunny hours: 4380 hours
   Annual total sunny hours: 3213 hours (rate: 0.73)
   Average daily radiation: 19.1 $MJ.m^{-2}.d^{-1}$

c. Water budget
   Cumulative precipitation over evaporation: 0.22

Table 4.25. Overview of weather data of Coria del Rio (1993 and 1994):

Stats	Tmax	Tmin	Ampl	SunH	DL	Rad	PREC	E0	RHA	Wind
minimum:	10.0	-2.0	2.5	0.0	9.4	2.6	0	0.5	0.24	0.4
maximum:	43.5	25.0	27.0	13.1	14.6	31.0	39	8.5	0.98	3.8
average:	25.1	11.7	13.4	8.8	12.0	19.1	n.r.	3.6	0.61	1.4
sum:	9167	4265	4903	3213	4380	6346	282	1302	n.r.	n.r.

where Tmax, Tmin and Ampl are in °C.
SunH and DL are in $h.d^{-1}$.
Rad is in $MJ.m^{-2}.d^{-1}$.
PREC and E0 are in $mm.d^{-1}$.
Wind is in $m.s^{-1}$.
n.r. is not relevant.

Management data

The management information required is not on disk file but is input from the keyboard. It defines the initial state of the system (at germination) and the applications and timing of irrigation.

PSint: the matric suction of the root environment at the moment of crop emergence (cm) is inferred from the initial soil moisture content through the moisture retention relation (pF curve). PSIint was 1000 cm in 1993 and 1200 cm in 1994.

ASSC: the actual surface storage capacity (cm) represents the equivalent water layer that can be stored on top of the land; it is a function of the slope and surface properties of the land. For flat land (less than 1°) and a soil surface prepared for furrow irrigation, the ASSC is around 10 cm.

SSint: the actual storage of water on top of the soil at the time of emergence (cm) was nil in both years.

ZTint: the depth of the phreatic level at the time of emergence (cm) is irrelevant to the present study because groundwater was always deep. The water level in a nearby well was at 5 meters deep. There is no forced drainage; the water table depth varies over the season (FIXZT$ is V).

Irrigation timing and depth: The gross application of irrigation water was measured at each irrigation. The efficiency of application must be estimated to quantify the effective rate of irrigation. Doorenbos and Pruitt (1977) suggest an indicative field application efficiency on loamy soils of 0.7. Table 4.26 presents net irrigation applications and the times of application in days after emergence (DaE) for the "WET" and "HALF" wet scenarios tested at Coria del Rio in 1993 and 1994.

Table 4.26. Net irrigation (mm) and irrigation timing (days after emergence) in Coria del Rio, 1993 and 1994.

1993			1994		
DaE (Days)	WET (mm)	HALF (mm)	DaE (Days)	WET (mm)	HALF (mm)
57	47	47	45	40	44
64	29		69	29	
71	33	33	74	21	31
78	34		81	30	
86	32		88	26	40
92	27	31	95	29	
99	27		102	26	
Total	229	111	Total	201	115

4.4. Model calibration and sensitivity testing

The "state variable approach" assumes that state variables characterize the system during a specific time interval. Their values are adjusted after each set of interval calculations to describe the state of the system in the next interval. The relationships used are based on knowledge of underlying biological, physiological and physical processes.

Forcing variables (or driving variables) characterize the influence of external factors on the system, and are not influenced by the processes within the system. Weather data are examples.

State variables characterize the system under study. They are the result of calculations, as is the case with 'dry organ mass' or 'soil water content'.

Rate variables indicate the rate at which state variables change: they reflect the dynamics of the processes involved. Examples are the rates of evaporation and transpiration. Constant values have been substituted for some rate variables (crop and soil constants). Some of these constants are system-specific, e.g. soil porosity or maximum rooting depth. Other constants are generic and taken from literature, for example the light use efficiency or the minimum permissible temperature.

The calculations commence with crop emergence, when the relative development stage is nil. State variables are attributed initial values inferred from e.g. the amount of seed used and the date and depth of sowing. Soil moisture conditions must be known as well.

Simulation continues until the crop cycle is complete, i.e. when the temperature sum required for full development is attained (at relative development stage 1.0). The calculations are aborted if weather conditions do not fulfil minimum crop requirements. Basic data required for different production situations, their data types and sources are listed in Table 4.27. All weather data are daily data; source 'Meteo' refers to a particular meteorological station. Each site is identified by a name (SoilLabel$) and referenced by its geographic coordinates: latitude (LAT), longitude (LON) and altitude (ALT). Every crop, variety or cultivar is identified by a name (CropLabel$).

Table 4.27. Basic data required for analyses of production situations.

Symbol	Description	Prod. PS1	Situation PS2	PS3	Data type	Source
1. Weather						
Tmax	maximum temperature	*	*	*	Forcing variable	Meteo
Tmin	minimum temperature	*	*	*	Forcing variable	Meteo
PREC	precipitation		*	*	Forcing variable	Meteo
RHA	relative air humidity	*	*	*	Forcing variable	Meteo
SunH	sun hours in the day	*	*	*	Forcing variable	Meteo
Wind	wind speed		*	*	Forcing variable	Meteo
2. Crop						
C3C4$	C3 or C4 plant	*	*	*	Constant	Literature
TO	threshold temperature	*	*	*	Constant	Measured
TSUM	temperature requirement	*	*	*	Constant	Measured
TLEAF	leaf temp. requirement	*	*	*	Constant	Measured
TLOW	lowest temperature	*	*	*	Constant	Literature
RDSroot	root growth ceases		*	*	Constant	Measured
RDm	maximum rooting depth		*	*	Constant	Measured
RDint	initial rooting depth		*	*	Constant	Measured
PSIleaf	critical leaf water head		*	*	Constant	Measured
SLAmax	max. specific leaf area	*	*	*	Constant	Measured
SLAmin	min. specific leaf area	*	*	*	Constant	Measured
ke	extinction coefficient	*	*	*	Constant	Measured
EFF	light use efficiency	*	*	*	Constant	Literature
TCM	max. turbulence coeff.		*	*	Constant	Literature
r(org)	maintenance respiration	*	*	*	Constant	Literature
EC(org)	conversion factor	*	*	*	Constant	Literature
fr(org)	allocation fraction	*	*	*	Rate variable	Measured
NSO	nitrogen in s.o.			*	Constant	Measured
NSTRAW	nitrogen in straw			*	Constant	Measured
PSO	phosphorous in s.o.			*	Constant	Measured
PSTRAW	phosphorous in straw			*	Constant	Measured
3. Soil						
SMO	total pore space		*	*	Constant	Measured
GAM	geometry factor		*	*	Constant	Measured
PSImax	boundary suction		*	*	Constant	Measured
KO	sat. hydraulic conduct.		*	*	Constant	Measured
ALFA	low suction parameter		*	*	Constant	Measured
AK	high suction parameter		*	*	Constant	Measured
SO	reference sorptivity		*	*	Constant	Measured
Ktr	transmission rate		*	*	Constant	Measured
4. Management						
GERDAY	day of germination	*	*	*		
SEED	rate of seed use	*	*	*	Values in this	
PSint	initial matric suction		*	*		
ASSC	act. surface storage cap.		*	*	set of data are	
SSint	initial surface storage		*	*		
ZTint	initial water table depth		*	*	management	
fixZT$	fixed or var. water table		*	*		
IEDAY	irrigation day		*	*	decisions	
IE	net irrigation gift		*	*		

Production situation 1 (PS1)

In Chapter 4.1 four main processes in PS1 calculations were considered. Now they are reviewed with emphasis on the variables in each process:

a. Production of assimilates as a function of PAR, DL, LAI, AMAX, EFF and Ke.

Day length (DL) was calculated (as a function of the latitude of the place and the day in the year. The procedure used is described in Chapter 4.2 (Radiation and evapotranspiration).

The leaf area index (LAI) and the extinction coefficient (Ke) were measured. LAI and leaf dry mass are related through the specific leaf area (SLA). This is a rate variable which normally decreases from a maximum value (SLAmax) at emergence to a minimum value (SLAmin) at maturity. This function was obtained by curve fitting and described in Chapter 4.3 (Data base).

The maximum rate of assimilation (AMAX) and the light use efficiency (EFF) were discussed in Chapter 4.2 (AMAX). The EFF value taken from literature is 0.5 $kg.ha^{-1}.h^{-1}/J.m^{-2}.s^{-1}$. AMAX is temperature dependent, calculated from a weighted reference temperature between 15 and 30 °C.

The photosynthetically active radiation (PAR) is a forcing variable calculated as a fraction of the total radiation. The calculation procedure is described in Chapter 4.2 (Radiation and evapotranspiration).

b. Allocation of the assimilates produced to the various plant organs. The (fixed) partitioning fractions are defined as a function of the development stage. See Chapter 4.2 (Dry matter partitioning). Different partitioning patterns will be discussed in this chapter.

c. Loss of assimilates in respiration to maintain living plant mass. Maintenance respiration = r(org) * S(org) * CfTemp , with r(org) expressed as a fraction of the standing organ dry mass (S(org)). The relative maintenance costs r(org) were discussed in Chapter 4.3 (Data base). The values were taken from literature.

d. Conversion of the remaining assimilates to structural plant matter. The efficiency of conversion (EC(org)) was discussed in Chapter 4.3 (Data base); no further evaluation seems to be required.

Evaluation of PS1 calculations includes sensitivity analysis done on the following variables:
- Photosynthetically active radiation (PAR)
- Average daily temperature
- Specific leaf area
- Maximum rate of assimilation
- Different partitioning patterns
- Relative maintenance costs

<u>The effect of the photosynthetically active radiation (PAR)</u>

The calculation of PAR use the daily number of sun hours (SunH) as an indication of daily available solar radiation. The data on SunH are assumed to be accurate to within 10%. Evaluation of measured and calculated radiations in Coria del Rio showed a difference of only 3 %. The conversion factor from incoming radiation to PAR was set to 0.5 (some other authors set this factor to 0.45). Three scenarios were run: (1) with the calculated PAR value; (2) 10 % greater and (3) 10 % less. The results of these runs are shown in Table 4.28.

Table 4.28. Results of program runs with 3 levels of PAR.

Level	LPG	Yield	HI	LAImax	LAIfinal	LAD	AMAXavg
(1993)							
0.9*PAR	105	4131	0.40	3.64	0.89	164	38.7
PAR	**105**	**4513**	**0.40**	**4.06**	**0.90**	**185**	**38.7**
1.1*PAR	105	4848	0.39	4.44	0.89	204	38.7
(1994)							
0.9*PAR	105	3883	0.40	3.26	0.80	153	38.7
PAR	**105**	**4271**	**0.40**	**3.67**	**0.82**	**174**	**38.7**
1.1*PAR	105	4613	0.40	4.04	0.83	192	38.7

where LPG is length of plant growth (days).
Yield is seed dry weight ($kg.ha^{-1}$).
HI is above ground harvest index ($kg_{seed}.kg^{-1}_{dry\ matter}$).
LAImax is maximum obtained LAI ($m^2.m^{-2}$).
LAIfinal is LAI at maturation ($m^2.m^{-2}$).
LAD is leaf area duration ($m^2.d$).
AMAXavg is average AMAX for the entire growing period ($kg.ha^{-1}.d^{-1}$).
The standard results for each of the years of study are in bold letters.

Table 4.28 shows that yields increase with increasing radiation levels. This same trend is shown by the LAD-values, but the rate of change is slightly less than the rate of variation of PAR. Harvest index and LAI are not affected by inaccuracies in PAR estimates.

The effect of temperature

As mentioned in Chapter 4.2 (Temperature), different daily temperatures are generated with different methods of calculation. Three scenarios were evaluated viz: using the calculated average temperature; 2 degrees higher than the average temperature and 2 degrees lower than average. The results generated for these three scenarios are shown in Table 4.29.

Table 4.29. Results of program runs with 3 average daily temperature values.

Level	LPG	Yield	HI	LAImax	LAIfinal	LAD	AMAXavg
(1993)							
Tavg-2 °C	115	4453	0.36	4.97	0.42	242	36.9
Tavg	**105**	**4513**	**0.40**	**4.06**	**0.90**	**185**	**38.7**
Tavg+2 °C	96	4249	0.42	3.35	1.05	142	40.9
(1994)							
Tavg-2 °C	116	4409	0.37	4.63	0.57	116	36.9
Tavg	**105**	**4271**	**0.40**	**3.67**	**0.82**	**174**	**38.7**
Tavg+2 °C	96	4026	0.42	3.05	1.15	135	41.0

where the variables are the same as in Table 4.28.

Differences of 2 °C caused between 1 and 6 % difference in yield and changed the length of the crop cycle by 10 days.

The effect of specific leaf area (SLA)

The specific leaf area decreases with increasing plant development, between the limits set by a maximum SLA-value (SLAmax) and a minimum SLA-value (SLAmin). Different varieties may have different SLAmax and SLAmin values. Several equations have been suggested to describe the relation between SLA and development stage.

Extreme values observed in the field were SLAmax between 19 and 24 $m^2.kg^{-1}$ dry leaf mass, and a SLAmin between 10 and 14 $m^2.kg^{-1}$. The function used was a logarithmic-one, alongside an alternative equation smoothing the logarithm by a factor 0.5. The use of five SLAmax and SLAmin values and two functions led to the ten combinations listed in Table 4.30:

Table 4.30. Combination of SLA functions.

Level	SLAmax	SLAmin	Equation
A	24	14	1) SLA = SLAmin - (SLAmax - SLAmin)*Log(RDS)
B	24	10	1) SLA = SLAmin - (SLAmax - SLAmin)*Log(RDS)
C	20	14	1) SLA = SLAmin - (SLAmax - SLAmin)*Log(RDS)
D	20	10	1) SLA = SLAmin - (SLAmax - SLAmin)*Log(RDS)
E	19	12	1) SLA = SLAmin - (SLAmax - SLAmin)*Log(RDS)
F	24	14	2) SLA = SLAmin - 0.5 * (SLAmax - SLAmin)*Log(RDS)
G	24	10	2) SLA = SLAmin - 0.5 * (SLAmax - SLAmin)*Log(RDS)
H	20	14	2) SLA = SLAmin - 0.5 * (SLAmax - SLAmin)*Log(RDS)
I	20	10	2) SLA = SLAmin - 0.5 * (SLAmax - SLAmin)*Log(RDS)
J	19	12	2) SLA = SLAmin - 0.5 * (SLAmax - SLAmin)*Log(RDS)

Results of program runs with these ten scenarios are presented in Table 4.31.

Table 4.31. Results of program runs with 10 levels of SLA.

Level	LPG	Yield	HI	LAImax	LAIfinal	LAD	AMAXavg
(1993)							
A	105	4357	0.34	6.88	0.12	332	38.7
B	105	4037	0.33	6.61	0.05	303	38.7
C	105	4721	0.39	4.88	0.86	227	38.7
D	105	4278	0.38	4.26	0.56	199	38.7
E	**105**	**4513**	**0.40**	**4.06**	**0.90**	**185**	**38.7**
F	105	4426	0.35	5.36	0.32	269	38.7
G	105	3987	0.35	4.30	0.24	214	38.7
H	105	4641	0.40	4.09	1.06	185	38.7
I	105	3822	0.39	2.79	0.69	128	38.7
J	105	4174	0.41	3.02	0.99	134	38.7
(1994)							
A	105	4192	0.35	6.23	0.01	322	38.7
B	105	3894	0.33	6.01	0.00	294	38.7
C	105	4508	0.39	4.46	0.79	216	38.7
D	105	4063	0.38	3.91	0.50	188	38.7
E	**105**	**4271**	**0.40**	**3.67**	**0.82**	**174**	**38.7**
F	105	4244	0.36	4.99	0.22	258	38.7
G	105	3793	0.35	3.93	0.17	203	38.7
H	105	4391	0.41	3.70	0.97	173	38.7
I	105	3509	0.40	2.43	0.60	117	38.7
J	105	3859	0.42	2.70	0.87	123	38.7

where the variables are the same as in Table 4.28.

The two types of equation (equations 1 and 2 in Table 4.30) give almost the same results in terms of yield. Differences in SLAmax and SLAmin values result in up to 25 % difference in yield. With the first equation there is a faster build-up of leaf area; with the second equation it is smoother. The leaf area duration (LAD) shows these differences best.

The effect of calculation of the maximum rate of assimilation (AMAX)

The maximum rate of assimilation is co-determined by a 'reference temperature', defined as the weighted averaged daytime temperature over the past ten days, with a minimum of 15 °C and a maximum of 30 °C.

The actual assimilation rate was inferred from partial harvests data and compared with the maximum assimilation rate. The following scenarios will be examined:
1) AMAX calculated by the 'normal' procedure
2) AMAX calculated without limits to the reference temperature range.

The results of program runs with these two scenarios are shown in Table 4.32.

Table 4.32. Results of program runs with 2 methods for estimating AMAX.

Level	LPG	Yield	HI	LAImax	LAIfinal	LAD	AMAXavg
(1993)							
AMAX	**105**	**4513**	**0.40**	**4.06**	**0.90**	**185**	**38.7**
limits	105	4513	0.40	4.05	0.91	184	38.6
(1994)							
AMAX	**105**	**4271**	**0.40**	**3.67**	**0.82**	**174**	**38.7**
limits	105	4294	0.40	3.67	0.82	174	38.8

where the variables are the same as in Table 4.28.

These results sre almost identical which suggests that no temperature limits were exceeded.

The effect of changes in assimilate partitioning (fr(org))

The partitioning fractions where calculated from partial harvests measurements, which show some variance between replications. Some of these differences were examined in the following scenarios:

A. the calculated fractionings.
B. Increase fr(Leaf) by 5 % at the expense of fr(Stem).
C. Increase fr(Stem) by 5 % at the expense of fr(Leaf).
D. Increase fr(Root) by 5 % at the expense of fr(Stem).
E. Increase fr(s.o.) by 10 % at the expense of fr(Stem) and fr(Leaf).
F. Let fr(s.o.) > 0 two weeks earlier.
G. Postpone fr(s.o.)>0 by 15 days.

These scenarios are thought relevant for the following crop varieties/types:

A. are the measured values.
B. for a "leafy" variety: a larger leaf to stem ratio.
C. for a "stemmy" variety: a smaller leaf to stem ratio.
D. for a "drier" variety: more allocation to roots.
E. for a "richer" variety: redirect more allocation to s.o.

F. for a "earlier" variety: earlier allocation to s.o.
G. for a "later" variety: later allocation to s.o.

The results of runs with these seven scenarios are shown in Table 4.33.

Table 4.33. Runs with 8 levels of fr(org).

Level	LPG	Yield	HI	LAImax	LAIfinal	LAD	AMAXavg
(1993)							
A	**105**	**4513**	**0.40**	**4.06**	**0.90**	**185**	**38.7**
B	105	4627	0.39	5.10	0.67	240	38.7
C	105	4062	0.40	2.88	0.94	128	38.7
D	105	4513	0.41	4.06	0.90	185	38.7
E	105	4355	0.44	3.34	0.30	148	38.7
F	105	4450	0.41	3.45	1.05	153	38.7
G	105	4514	0.39	4.71	0.95	212	38.7
(1994)							
A	**105**	**4271**	**0.40**	**3.67**	**0.82**	**174**	**38.7**
B	105	4428	0.39	4.74	0.60	229	38.7
C	105	3744	0.41	2.54	0.83	117	38.7
D	105	4271	0.42	3.67	0.82	174	38.7
E	105	4051	0.44	3.03	0.25	137	38.7
F	105	4171	0.41	3.11	0.94	143	38.7
G	105	4300	0.39	4.37	0.88	201	38.7

where the variables are the same as in Table 4.28.

Yields vary between 1.03 and 0.90 times the yield of level A in 1993 and between 1.04 and 0.88 in 1994. LAImax and LAD values show similar variation; these differences are caused by different values of fr(leaf).

Almost no differences in yield are observed between levels F and G. Evidently, a difference of one month in the initiation of the storage organ (15 days earlier or 15 days later) can be compensated by longer allocation to the storage organ (in the case of level F) or by longer LAD (in the case of level G).

The effect of relative maintenance requirements (r(org))

Relative maintenance requirements (r(org)) were borrowed from literature where standard values were found that apply at optimal temperature and for various development stages. There are indications that maintenance requirements are (partly) dependent on the availability of water. To merge these options the following scenarios were examined:

1) r(org) as proposed in Chapter 4.3 (Data base).
2) r(org) as proposed in literature.
3) r(org) as in 2) with r(s.o.) set to zero after flowering.

The values emerging from these three combinations are shown in Table 4.34.

Table 4.34. r(org) values obtained with various approaches.

Scenario	r(Root)	r(Stem)	r(Leaf)	r(s.o.)	Observations
1	0.01	0.0075	0.05	0.023	
2	0.01	0.0075	0.015	0.023	literature data
3	0.01	0.0075	0.01	0.023	r(s.o.) = 0 at RDS >= 0.55

Results of runs with these three scenarios are shown in Table 4.35.

Table 4.35. Results generated using 3 sets of r(org)-values.

Level	LPG	Yield	HI	LAImax	LAIfinal	LAD	AMAXavg
(1993)							
1	**105**	**4513**	**0.40**	**4.06**	**0.90**	**185**	**38.7**
2	105	5452	0.33	7.54	3.32	368	38.7
3	105	5545	0.43	4.06	0.90	185	38.7
(1994)							
1	**105**	**4271**	**0.40**	**3.67**	**0.82**	**174**	**38.7**
2	105	5255	0.33	7.08	3.18	354	38.7
3	105	5299	0.44	3.67	0.82	174	38.7

where the variables are the same as in Table 4.28.

The results show differences in yield of up to 25 % and a strong effect of r(leaf). A low r(leaf)-value affects the LAD-value of scenario 2; LAI-value at maturity of > 3 is clearly too high. The differences with level 3 are explained by the absence of maintenance respiration.

Varietal differences

Differences between varieties can be evaluated along the same lines as done previously for differences in specific leaf area (Table 4.31), differences in fractioning (Table 4.33) and differences in maintenance respiration (Table 4.35). Two other crop characteristics are variety-specific: the heat requirement for full plant development (TSUM), and the heat requirement for full leaf development (TLEAF).

In Chapter 4.3 (Data base) it was described how indicative values for several crop characteristics are obtained. These values are approximate. Different varieties may have different TSUM and TLEAF values. To evaluate the effects of such differences an increase/decrease of 10 % of TSUM was introduced in the calculations keeping the TLEAF/TSUM ratio constant, and an increase/decrease of 10 % of TLEAF keeping TSUM constant. This leads to the five combinations presented in Table 4.36:

Table 4.36. Calculated effects of several TSUM and TLEAF values.

Level	TSUM	TLEAF	Ratio	Observations
A	1470	900	0.61	Measured values
B	1617	990	0.61	Increase by 10 % (both)
C	1323	810	0.61	Decrease by 10 % (both)
D	1470	990	0.67	Increase by 10 % (TLEAF)
E	1470	810	0.55	Decrease by 10 % (TLEAF)

The results of runs with these five scenarios are shown in Table 4.37:

Table 4.37. Results of runs with several TSUM and TLEAF values.

Level	LPG	Yield	HI	LAImax	LAIfinal	LAD	AMAXavg
(1993)							
A	**105**	**4513**	**0.40**	**4.06**	**0.90**	**185**	**38.7**
B	112	4746	0.38	4.84	0.51	235	39.6
C	98	4008	0.41	3.16	1.14	135	37.7
D	105	4744	0.41	4.07	1.49	190	38.7
E	105	4100	0.37	4.05	0.33	177	38.7
(1994)							
A	**105**	**4271**	**0.40**	**3.67**	**0.82**	**174**	**38.7**
B	112	4555	0.38	4.42	0.58	222	39.6
C	98	3762	0.42	2.86	1.13	125	37.7
D	105	4486	0.41	3.67	1.44	178	38.7
E	105	3932	0.38	3.66	0.51	167	38.7

where the variables are the same as in Table 4.28.

Differences in yield are correlated with differences in LAD-values. Decreasing LAD led to yield reductions between 8 and 12 %; increasing LAD caused yield increases between 5 and 7 %. The calculated LPG differed from the period measured by plus or minus 7 days.

in the water balance model are those characterizing:

soil

SI) for low suction (4.68a)
suction (4.68b)

|

(4.65)

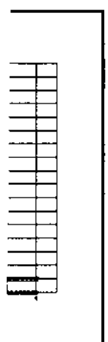
il

(4.71)
- SMPSI / SMO) (4.72)

tes of water fluxes in soil. The main goal of the water soil moisture content over the crop season and derive the ɔr crop production.

ity parameters

ꞩ2 scenarios were often quite different from measured field ugh adjustment of soil parameter values proved futile. The state variables values over the crop season, where SMPSI WATER is water sufficiency (-), TR is actual rate of maximum rate of water uptake by roots ($cm.d^{-1}$). Note the WATER values.



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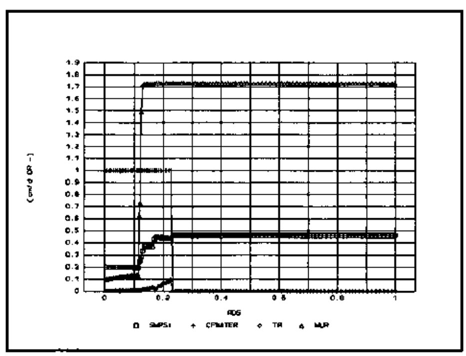


Fig. 4.33. Water budget at low hydraulic soil conductivity.

ɪductivities in figures 4.35 and 4.36 are defined by the ig. 4.32, AK=36 $cm^{-2.4}.d^{-1}$, n=1.4 and PSImax=181 cm; =2.1 and PSImax=305 cm. Values of PSImax indicate the ɩ. 4.68a) to 'high suction' (eqn. 4.68b). Changes in the low at soil suction values (far) beyond the PSImax value. This suggests that one or more parameter values must be changed. In this case the value of n was varied between 1.4 (recommended for all soil materials) and 2.1 (curve fitting).

ERRATA

Page 107, line 23: figures 4.35 and 4.36 **should be** figures 4.32 and 4.33

Page 109, line 10: equations 4.70 and 4.71 **should be** equations 4.68a and 4.68b

Page 109, line 12: equation 4.76 **should be** equation 4.73

Page 109, lines 14 and 15: graphs 4.39 and 4.40 **should be** graphs 4.36 and 4.37

In Fig. 4.32, CFWATER drops almost instantaneously from one (stress-free) to zero in response to a sharp drop in maximum uptake rate (MUR). In Fig. 4.33 transpiration is halted by soil saturation.

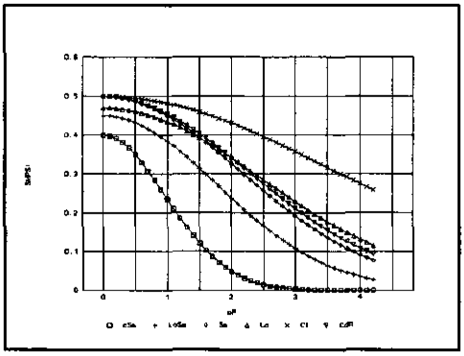
The actual rate of transpiration (TR) is found by matching water supply to the roots (MUR) with demand (TRM). The supply side represents the water available for transpiration: it depends on crop characteristics, crop development, and soil moisture content and soil hydraulics. The water required for maximum transpiration represents the demand side: it depends on environmental conditions and on crop characteristics and development. In Fig. 4.32, soil suction reached the PSIleaf value and consequently the MUR value dropped to nil. In Fig. 4.33, the fluxes are so slow that water entering the system (in this case 9.2 cm of precipitation) increased the soil moisture content sharply until saturation.

To explain these two extremes, the soil data was compared with default soil data suggested for main textural classes (Driessen and Konijn, 1992).

Table 4.38. Indicative values for soil constants for reference soil texture classes and Coria del Rio soil.

Texture class	Coarse sands	Loamy sands	Sandy loams	Loams	Clays	Coria loam
SMO	0.4	0.45	0.5	0.47	0.5	0.5
GAM	0.1	0.03	0.02	0.015	0.007	0.018
KO	650	150	60	20	3	24
ALFA	0.15	0.07	0.05	0.04	0.03	0.038
PSImax	100	130	155	170	260	305
AK	0.1	13	30	30	3	36
SO	50	20	17	17	5	10.78
Ktr	430	100	40	14	2	4.8

Using these constants and the equations for hydraulic conductivity (4.68a and 4.68b) and soil moisture content (4.65), the next two figures are constructed.



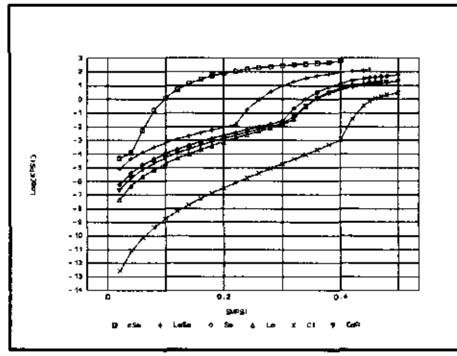
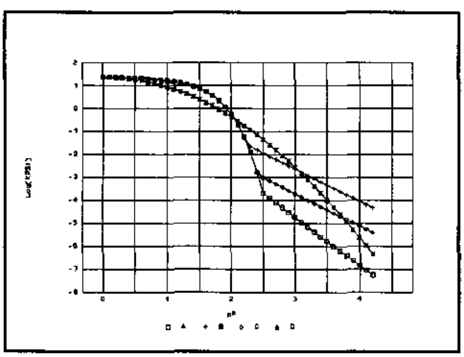


Fig. 4.34. SMPSI-PSI curves. **Fig. 4.35.** KPSI-SMPSI curves.
where the texture class cSa is coarse sand, LoSa is loamy sand, Sa is sand, Lo is loam, Cl is clay and CdR is the soil at Coria del Rio.

These two figures show that Coria del Rio soil behaves according to its textural class, both in terms of soil moisture content and hydraulic conductivity. Adjustment of soil parameters values and use of alternative soil conductivity equations produced the next figures: Fig. 4.36 shows LOG(KPSI) as a function of LOG(PSI) and Fig. 4.37 shows KPSI as a function of SMPSI.



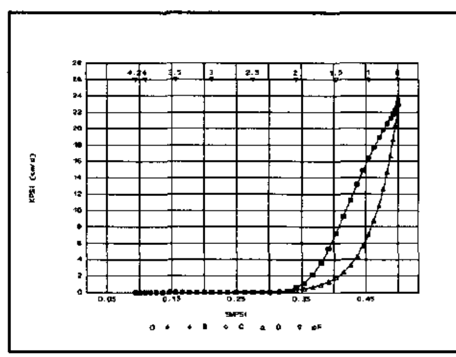


Fig. 4.36. KPSI-PSI curves. **Fig. 4.37.** KPSI-SMPSI curves.
Curves A, B and C are KPSI functions as in equations 4.70 and 4.71; curve A with AK= 36 and n=1.4; curve B with AK=36 and n=2.1; curve C with AK=3 and n=1.4. Curve D is a KPSI function of the type of equation 4.76, with ALFA=0.19.

The explanation for the sharp changes in water balance variables can be seen in graphs 4.39 and 4.40. The problem is greatest in the pF range between 2 and 3. In the formal curve (A) the drop in KPSI is very steep. Attempts to smoothen the curve by means of 2 step equations bring no relief. Data obtained with the hot air method suggest a linear relationship beyond pF=3.2. Recall that KSPI values were obtained with measurements at PSI 50, 150, 500 and 1000 cm (pF 3) and extrapolated from thereon to higher PSI-values, i.e. to PSI values as occur in the cropping season. The differences between the curves A, B and C in Fig. 4.36 are evident despite the use of log scales, but such differences do not show up in Fig. 4.37.

There is evidently considerable variation in soil parameter values; soil sampling and sample treatment may explain part of the difference. The following table (Driessen, 1995) list generic values for construction of the hydraulic conductivity function (from literature).

Table 4.39. Generic values for the saturated hydraulic conductivity (K(sat) in $cm.d^{-1}$) and for geometry coefficient ALFA (cm^{-1}) as suggested by Rijtema (1969), Rawls et al. (1982), Carsel & Parrish (1988) and Wösten (1987).

Texture class	Rijtema (1969)		Rawls et al. (1982)		Carsel & Parrish(1688)		Wösten (1987)	
	K(sat)	ALFA	K(sat)	ALFA	K(sat)	ALFA	K(sat)	ALFA
Sand	1120	0.2440	504.0	0.138	712.8	0.145	223.0	0.0524
Loamy sand	26.5	0.0398	146.6	0.115	350.2	0.124	63.90	0.0182
Sandy loam	12	0.0248	62.16	0.068	106.1	0.075	53.10	0.0216
(Loess) loam	14.5	0.0490	16.32	0.090	24.96	0.036	25.60	0.0231
Silty loam	6.5	0.0200	31.68	0.048	10.80	0.020	24.00	0.0280
Sandy clayloam	23.5	0.0353	10.32	0.036	31.44	0.059	n.d.	n.d.
Clayloam	0.98	0.0248	5.52	0.039	6.24	0.019	n.d.	n.d.
Silty clayloam	1.5	0.0237	3.60	0.031	1.68	0.010	n.d.	n.d.
Sandy clay	3.5	0.0274	2.88	0.034	2.88	0.027	n.d.	n.d.
Silt clay	1.3	0.0480	2.16	0.029	0.48	0.005	n.d.	n.d.
Clay	0.22	0.0380	1.44	0.027	4.80	0.008	n.d.	n.d.

n.d. is not determined.

Ranges and absolute values assigned to each texture class vary widely between the authors. A source of the differences may be in the determination of texture: "total clay contents" determined in the laboratory may differ significantly from field estimates of "natural clay". Less but broader texture classes would be adequate.

Considering the uncertainties associated with measured KPSI-data, a mathematical function for the description of KPSI is proposed that has the same structure as the moisture retention equation (4.65):

$$KPSI = K0 * PSI^{-ALFA * \ln(PSI)} \qquad (4.73)$$

where ALFA = 0.19 cm^{-2}.

This equation produced the D curves in figures 4.39 and 4.40.

The figures 4.41 through 4.46 show the soil moisture content (SMPSI), the coefficient of water availability (CFWATER) the actual transpiration rate (TR), and the maximum rate of water uptake by the root system (MUR) over time. These variables illustrate changes in the soil water budget at Coria del Rio in 1993 and 1994, calculated for three treatments (dry, half dry, wet), using eqn. 4.73 to describe the KPSI function.

The figures show clearly the effects of irrigations (three in the 'half dry' treatment and seven in the 'wet' treatment) on all parameters plotted.

Program runs:

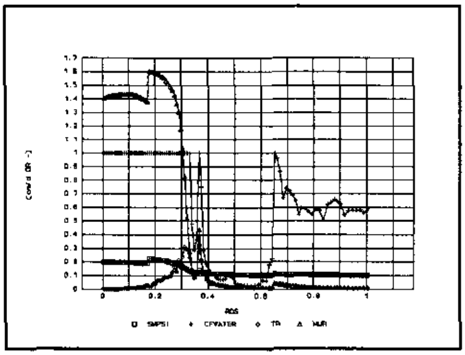


Fig. 4.38. Dry treatment 1993.

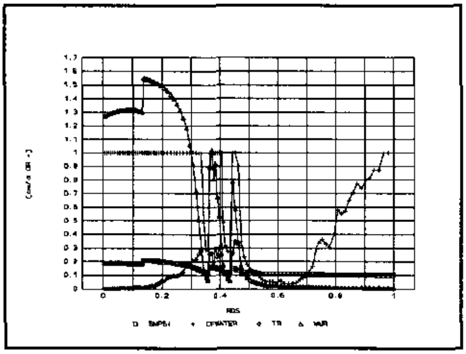


Fig. 4.39. Dry treatment 1994.

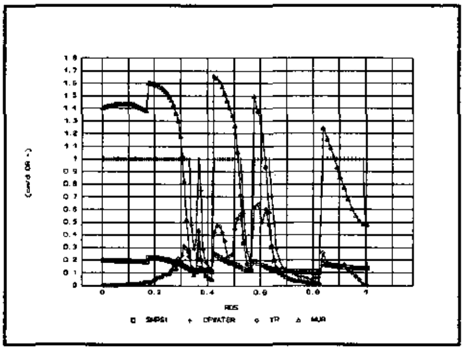


Fig. 4.40. Half treatment 1993.

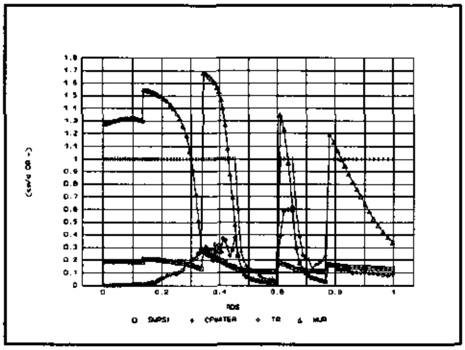


Fig. 4.41. Half treatment 1994.

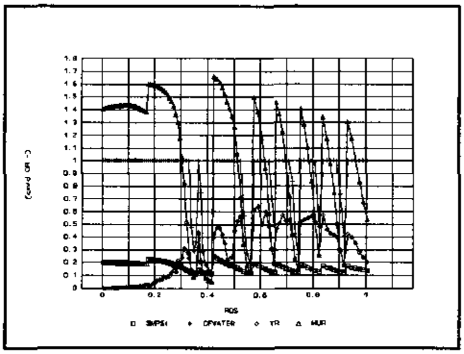


Fig. 4.42. Wet treatment 1993.

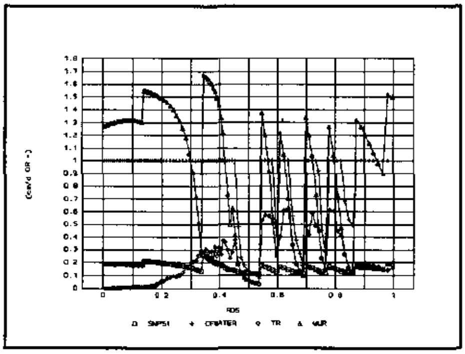


Fig. 4.43. Wet treatment 1994.

Where SMPSI is soil moisture content (-), CFWATER is sufficiency of water availability (-), TR is transpiration rate ($cm.d^{-1}$), and MUR is maximum uptake rate ($cm.d^{-1}$).

The effect of soil parameter values on system performance can be tested for more scenarios in PS2 calculations than in PS1 calculations; precipitation and irrigations at different rates and timing, can make the difference between production potential and crop failure. For this reason the program runs are examine for a fixed irrigation schedule: 3 applications of 4 cm each on days 45, 60 and 75 in the crop cycle. The initial soil suction was set at 1300 cm, and the emergence dates were 96 in 1993 and 85 in 1994.

Most soil constants for the Coria del Rio soil lie between the values suggested for the reference soil texture classes of 'clays' and 'loams' (Table 4.38). The SMPSI-PSI and KPSI-PSI curves are also between the curves calculated for these soil types (Figs. 4.34 and 4.35).

For the description of hydraulic conductivity, two soil parameters values are needed: the saturated hydraulic conductivity (K0) and the empirical constant (ALFA). The combinations listed in Table 4.40 were tested:

Table 4.40. Combinations of KPSI parameters tested.

Level	K0	ALFA	
A	**24**	**0.19**	**standard values**
B	26.4	0.19	10 % increase in K0
C	24	0.209	10 % increase in ALFA
D	21.6	0.19	10 % decrease in K0
E	24	0.171	10 % decrease in ALFA
F	26.4	0.209	10 % increase in K0 and ALFA
G	21.6	0.171	10 % decrease in K0 and ALFA

The results of program runs with these seven scenarios are presented in Table 4.41.

Table 4.41. Results of program runs for 7 combinations of K0 and ALFA.

Level	Yield	HI	LAImax	LAD	CFWone	SMPSI	sumTR	CFW
(1993)								
A	**1351**	**0.19**	**3.72**	**142**	**59**	**0.10**	**16.5**	**0.77**
B	1360	0.20	3.71	142	59	0.10	16.4	0.76
C	1404	0.20	3.83	148	60	0.11	17.3	0.80
D	1355	0.19	3.73	143	59	0.10	16.5	0.77
E	1215	0.19	3.55	134	58	0.10	15.2	0.75
F	1402	0.20	3.83	148	60	0.11	17.3	0.80
G	1247	0.19	3.55	134	58	0.10	15.2	0.74
(1994)								
A	**1166**	**0.19**	**3.26**	**125**	**44**	**0.10**	**14.4**	**0.75**
B	1162	0.19	3.26	125	44	0.10	14.4	0.75
C	1287	0.19	3.56	139	70	0.11	16.0	0.78
D	1165	0.19	3.33	128	44	0.10	14.6	0.75
E	986	0.17	3.28	123	45	0.10	13.5	0.75
F	1282	0.19	3.55	139	69	0.11	15.9	0.78
G	1003	0.17	3.28	123	45	0.10	13.6	0.75

where Yield is seed dry weight ($kg.ha^{-1}$).
HI is above ground harvest index ($kg_{seed}.kg^{-1}_{dry\ matter}$).
LAImax is maximum obtained LAI ($m^2.m^{-2}$).
LAD is leaf area duration ($m^2.d$).
CFWone is the first day with water stress in the crop cycle (d).
SMPSI is soil moisture content (-).
sumTR is cumulative actual transpiration (cm).
CFW is average of daily CFWATER values over the crop season (-).

Most of the variations in Table 4.41 is due to variations in the value of ALFA. A higher

ALFA value causes a lower KPSI and water stress will appear later in the season. A 10 % variation in K0 proved insignificant. Comparing the results for 1993 and 1994, one sees the same trend but at different levels explained by different precipitation patterns.

The effect of moisture retention parameters

The moisture retention curve is described by two constants: the total pore fraction (SM0) and an empirical constant (GAM). The following table (Driessen, 1995) lists generic values from literature.

Table 4.42. Generic values for soil constants SM0 and GAM, by texture class.

Texture class	SM0 ($cm^3.cm^{-3}$)	GAM (cm^{-2})
Sand	0.395	0.1000
Loamy sand	0.439	0.0330
Sandy loam	0.504	0.0207
(Loess) loam	0.455	0.0169
Silty loam	0.509	0.0185
Sandy clayloam	0.432	0.0098
Clayloam	0.445	0.0058
Silty clayloam	0.475	0.0105
Sandy clay	0.453	0.0085
Silt clay	0.507	0.0065
Clay	0.540	0.0042

Combinations of SM0 and GAM are listed in Table 4.43:

Table 4.43. Combinations of SM0 and GAM tested.

Level	SM0	GAM	
A	**0.50**	**0.018**	**standard values**
B	0.55	0.018	10 % increase in SM0
C	0.50	0.0198	10 % increase in GAM
D	0.45	0.018	10 % decrease in SM0
E	0.50	0.0162	10 % decrease in GAM
F	0.55	0.0198	10 % increase in SM0 and GAM
G	0.45	0.0162	10 % decrease in SM0 and GAM

The results of program runs with these seven scenarios are presented in Table 4.44.

Table 4.44. Results of program runs for 7 combinations of SM0 and GAM.

Level	Yield	HI	LAImax	LAD	CFWone	SMPSI	sumTR	CFW
(1993)								
A	**1351**	**0.19**	**3.72**	**142**	**59**	**0.10**	**16.5**	**0.77**
B	1372	0.20	3.75	144	59	0.11	16.7	0.77
C	1359	0.19	3.72	142	59	0.09	16.5	0.76
D	1350	0.19	3.70	141	59	0.09	16.3	0.76
E	1352	0.19	3.71	142	59	0.12	16.5	0.77
F	1361	0.19	3.75	144	59	0.10	16.7	0.78
G	1351	0.19	3.70	141	59	0.11	16.3	0.76

Table 4.44. Continuation.

Level	Yield	HI	LAImax	LAD	CFWone	SMPSI	sumTR	CFW
(1994)								
A	**1166**	**0.19**	**3.26**	**125**	**44**	**0.10**	**14.4**	**0.75**
B	1157	0.19	3.35	129	44	0.11	14.8	0.77
C	1151	0.19	3.29	126	44	0.09	14.5	0.75
D	1141	0.19	3.25	124	44	0.09	14.3	0.75
E	1169	0.19	3.26	125	44	0.12	14.5	0.75
F	1171	0.19	3.33	128	44	0.10	14.7	0.76
G	1147	0.19	3.22	123	44	0.11	14.3	0.75

where the variables are the same as in Table 4.41.

Table 4.44 shows only slight differences between the combinations tested. This confirms that the values of SM0 and GAM as shown in Table 4.42 could be aggregated to fewer but broader texture classes.

The effect of infiltration parameters

The maximum infiltration rate (IM) is described by the reference sorptivity (S0) and the hydraulic permeability of the transmission zone (Ktr). Varying the values of both parameters (S0 = 44 $cm.d^{-0.5}$ and Ktr = 20 $cm.d^{-1}$) 4-fold gave no differences in the program runs. The reason is that the maximum infiltration rate is at least equal to Ktr (eqn. 4.71) and increases with decreasing soil moisture content. At a low soil moisture content and little precipitation and irrigation (as is the case), the infiltration capacity of the soil will not be exceeded and runoff will not take place. Recall that the time interval used in the calculations (one day) is too long to detect small differences in precipitation and/or irrigation intensities. The results show that the proposed values of S0 = 10.78 $cm.d^{-0.5}$ and Ktr = 4.8 $cm.d^{-1}$ can be rounded to S0 = 11 $cm.d^{-0.5}$ and Ktr = 5 $cm.d^{-1}$ without any loss of accuracy.

The effect of evapo(trans)piration parameters

Varying the values of E0 and ET0 by 10, 20 and 30 % gives the combinations listed in Table 4.45:

Table 4.45. Combinations of E0 and ET0 values tested.

Level	E0 and ET0
A	**standard values**
B	10 % increase in E0 and ET0
C	10 % decrease in E0 and ET0
D	20 % increase in E0 and ET0
E	20 % decrease in E0 and ET0
F	30 % increase in E0 and ET0
G	30 % decrease in E0 and ET0

The results of program runs with these seven scenarios are presented in Table 4.46.

Table 4.46. Results of program runs for seven levels of E0 and ET0.

Level	Yield	HI	LAImax	LAD	CFWone	SMPSI	sumTR	CFW
(1993)								
A	**1351**	**0.19**	**3.72**	**142**	**59**	**0.10**	**16.5**	**0.77**
B	1211	0.19	3.55	133	58	0.10	16.6	0.74
C	1530	0.21	3.86	150	60	0.10	16.1	0.79
D	1032	0.17	3.41	126	57	0.10	16.7	0.76
E	1704	0.22	3.88	154	71	0.10	15.2	0.82
F	936	0.17	3.28	120	57	0.10	16.9	0.75
G	1853	0.23	3.88	157	71	0.10	14.0	0.86
(1994)								
A	**1166**	**0.19**	**3.26**	**125**	**44**	**0.10**	**14.4**	**0.75**
B	1042	0.18	3.20	121	44	0.10	15.0	0.74
C	1310	0.20	3.42	134	45	0.10	14.1	0.78
D	914	0.17	3.10	115	44	0.10	15.5	0.75
E	1264	0.21	3.14	123	63	0.10	11.4	0.76
F	840	0.16	2.98	110	43	0.10	15.9	0.73
G	1564	0.23	3.40	136	66	0.10	11.6	0.80

where the variables are the same as in Table 4.41.

Table 4.46 shows that a difference of 10 % in E0 and ET0-values causes a yield variation of less than 2 % in both years.

Varietal differences

Differences between varieties were evaluated at PS2-level for three crop characteristics: the critical leaf water head (PSIleaf), the maximum turbulence coefficient (TCM) and the maximum rooting depth (RDm). The relative performance of varieties grown under different water regimes suggests different PSIleaf values, as discussed in section 4.3, and the same holds for the TCM value, which was taken from literature. The RDm value seems to some extent dictated by plant and soil interactions. Sunflower develops a deeper rooting system in soils with low bulk density.

A 10 % variation in TCM value was tested for three PSIleaf values: 14000 cm, 17000 and 20000 cm. A shallow root system of 50 cm depth is pitched against a rooting depth of 150 cm. Seven combinations are presented in Table 4.47:

Table 4.47. Combinations of varietal differences.

Level	PSIleaf	TCM	RDm	
A	**14000**	**1.2**	**100**	**standard values**
B	17000	1.2	100	variation in PSIleaf
C	20000	1.2	100	variation in PSIleaf
D	14000	1.32	100	10 % increase in TCM
E	14000	1.08	100	10 % decrease in TCM
F	14000	1.2	50	variation in RDm
G	14000	1.2	150	variation in RDm

The results of test runs with these seven scenarios are presented in Table 4.48.

Table 4.48. Results of test runs for 7 combinations of PSIleaf, TCM and RDm.

Level	Yield	HI	LAImax	LAD	CFWone	SMPSI	sumTR	CFW
(1993)								
A	**1351**	**0.19**	**3.72**	**142**	**59**	**0.10**	**16.5**	**0.77**
B	1362	0.19	3.75	143	59	0.10	16.7	0.78
C	1378	0.20	3.77	144	60	0.10	16.8	0.78
D	1221	0.19	3.57	134	58	0.10	16.4	0.74
E	1525	0.21	3.85	150	60	0.10	16.4	0.79
F	1196	0.19	3.48	131	58	0.10	15.1	0.76
G	1453	0.20	3.85	150	70	0.10	17.7	0.80
(1994)								
A	**1166**	**0.19**	**3.26**	**125**	**44**	**0.10**	**14.4**	**0.75**
B	1175	0.19	3.31	127	44	0.10	14.6	0.75
C	1167	0.19	3.35	129	44	0.10	14.8	0.77
D	1041	0.18	3.17	120	44	0.10	14.7	0.74
E	1356	0.20	3.41	133	44	0.10	14.5	0.77
F	974	0.20	2.61	97	41	0.10	11.8	0.72
G	1266	0.19	3.51	138	69	0.10	15.9	0.79

where the variables are the same as in Table 4.41.

Variation of the PSIleaf value had only a minor effect. A greater PSIleaf-value is associated with a greater sumTR value, meaning that the crop was able to extract more water. Variation of the TCM value has the same effect as a variation of E0 and ET0 values. Variation of RDm changes the quantity of available water which causes the first day with water shortage (CFWone) to move back or forth. Yield increases with an increase in rooting depth if water is a limitation. The maximum rooting depth of a crop (variety) may be dictated by soil specifications, so that measurements are preferred over physiological estimates.

Summary of the PS2 sensitivity analysis

In total, 25 scenarios were tested. Most of the variables tested are soil parameters; E0 and ET0 were included because they are important components of the water budget.

To examine the full set of scenarios, 4 variables were taken as indicators; seed production (YIELD), leaf area duration (LAD), the first day in the crop cycle with water shortage (CFWone) and cumulative transpiration (sumTR).

Fig. 4.44 and Fig. 4.45 show the values generated for these four variables for each year. The data shown are ratios of each of the four variables with the standard results (scenario 1).

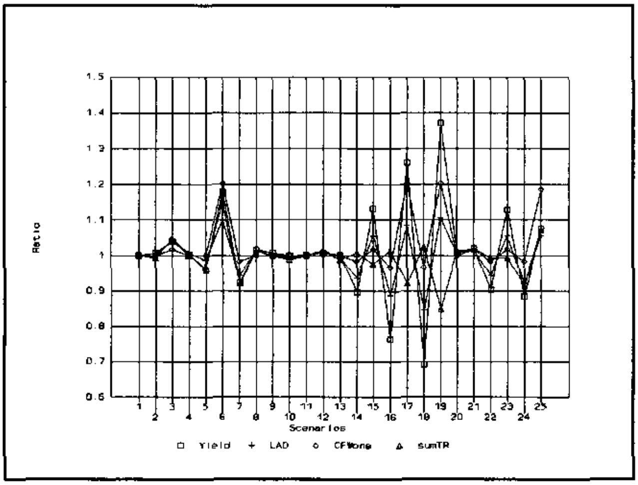


Fig. 4.44. Relative Yield, LAD, CFWone and sumTR variation for 25 scenarios in 1993.

The legend for each of these scenarios (numbers on the x-axis) is:

1: Standard values

2: KPSI-B (+10 % K0);	8: SMPSI-B (+10 % SM0)
3: KPSI-C (+10 % ALFA);	9: SMPSI-C (+10 % GAM)
4: KPSI-D (-10 % K0);	10: SMPSI-D (-10 % SM0)
5: KPSI-E (-10 % ALFA);	11: SMPSI-E (-10 % GAM)
6: KPSI-F (+10 % K0 & ALFA);	12: SMPSI-F (+10 % SM0 & GAM)
7: KPSI-G (-10 % K0 & ALFA);	13: SMPSI-G (-10 % SM0 & GAM)
14 E0&ET0-B (+10 % E0 & ET0);	20: VAR-B (+PSIleaf=17000)
15 E0&ET0-C (-10 % E0 & ET0);	21: VAR-C (+PSIleaf=20000)
16 E0&ET0-D (+20 % E0 & ET0);	22: VAR-D (+10 % TCM)
17 E0&ET0-E (-20 % E0 & ET0);	23: VAR-E (-10 % TCM)
18 E0&ET0-F (+30 % E0 & ET0);	24: VAR-F (-RDm=50)
19 E0&ET0-G (-30 % E0 & ET0);	25: VAR-G (+RDm=150)

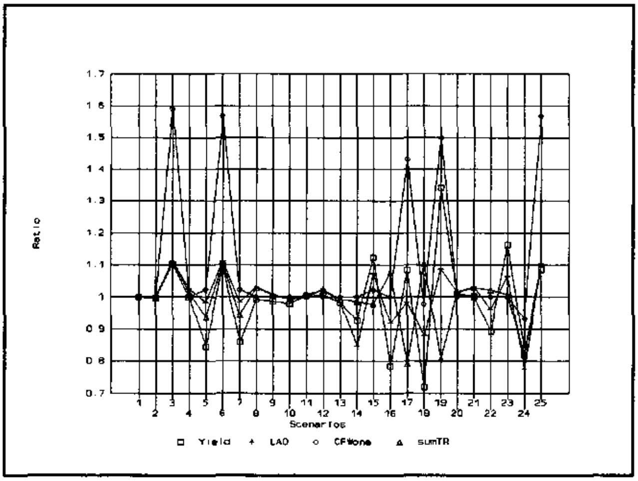


Fig. 4.45. Relative Yield, LAD, CFWone and sumTR variation for 25 scenarios in 1994.

Yields:
Variations in yield are predominantly associated with the KPSI function used and with the value of ALFA (scenarios 2, 5, 6 and 7). The other causes of variation are obvious: variations in demand (evapotranspiration level and TCM value); and supply (rooting depth). It is interesting to note that accuracy in evapotranspiration calculations is eventually very important.
Yield is generally well correlated with LAD, CFWone and sumTR but these relations are not linear: in 1994 the correlations with CFW and sumTR were weak or absent. The CFW value is the average of daily CFWATER values over the crop season, included in the outputs to demonstrate that indicative values for an entire crop cycle lead to gross misinterpretation by ignoring the effects of dynamics and interactions between factors.

LAD:
The LAD varies more at shallower rooting depths (scenario 24). A very good correlation was found between LAD and LAImax, which for practical reasons can be an indicator of crop performance to be used at field level. In both years the R^2 was 0.96.

CFWone:
The CFWone-value indicates the first day with water stress in the crop cycle. Variation of the CFWone-value is the result of interactions between all factors in the water balance: demand, supply, rates and timing.
Variations are likely to be greater in the case of a greater CFWone-value than at earlier stress, because the initial soil moisture content buffers initial water requirements. The most important factor affecting CFWone is the ALFA parameter in the KPSI function. The levels of E0 and ET0 and the RDm value also affect CFWone but only at greater variations of these parameters.

sumTR:
The cumulative actual transpiration (sumTR) represents, for all practical purposes, total water uptake by the crop. The closer it is to the potential uptake the better it correlates with yield. sumTR is positively correlated with E0 and ET0.

The generated fluctuations of Yield, LAD, CFWone and sumTR were normalized and are shown in Table 4.49. Note that the average value is around 1.0.

Table 4.49. Variations of generated Yield, LAD, CFWone and sumTR values relative to values obtained with standard parameter values.

Year	1993				1994			
Stats	Yield	LAD	CFWone	sumTR	Yield	LAD	CFWone	sumTR
maximum :	1.37	1.11	1.20	1.15	1.34	1.11	1.59	1.11
minimum :	0.69	0.85	0.97	0.85	0.72	0.78	0.93	0.79
average :	1.01	1.00	1.03	0.99	0.99	1.00	1.11	1.00
std.dev.:	0.14	0.06	0.08	0.06	0.13	0.08	0.22	0.08
c.v. (%):	14	6	7	6	13	8	19	8

The cumulative deviations of the eight output variables shown in Tables 4.41, 4.44, 4.46 and

4.48 from the standard output value (unity) are shown in Fig. 4.46 (values of both positive deviations and negative deviations were all made positive). Small variations are caused by changes in K0 (scenarios 2 and 4), SM0 and GAM (scenarios 8 to 13) and PSIleaf (scenarios 20 and 21). Greater variations are caused by changes in the values of ALFA (scenarios 3, 5, 6 and 7), E0 and ET0 (scenarios 14 and 15) and RDm (scenarios 24 and 25). Differences in E0 and ET0 do not produce a same variation in output: the level of variation is examined in scenarios 14, 16 and 18 or 15, 17 and 19; the direction of variation in scenarios 14 and 15, 16 and 17, 18 and 19.

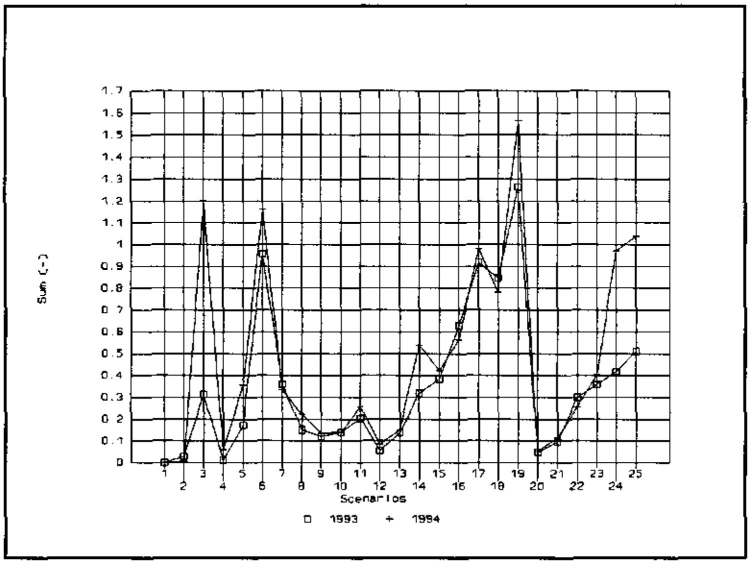


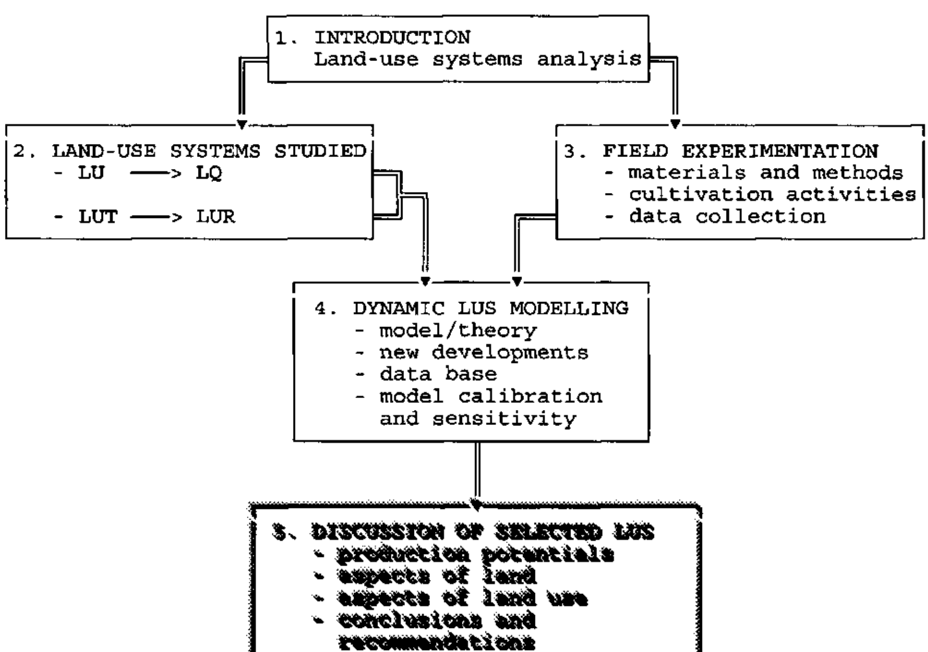
Fig. 4.46. Relative deviations of eight output variables in 25 scenarios for 1993 and 1994.
Legend of scenarios in caption of Fig. 4.44.

Differences are also seen between years: e.g. ALFA (scenario 3) and RDm (scenarios 24 and 25). The ratios between the absolute values of 1994 over 1993 are 0.86 for Yield, 0.88 for LAD, 0.75 for CFWone and 0.87 for sumTR.

The differences observed between 1994 and 1993 are to a considerable degree attributed to forcing variables.

The total precipitation within the cropping season was 10.5 cm in 1993 and 8.5 cm in 1994. In 1993, 50 % of the total had fallen at RDS = 0.25; in 1994 this happened at RDS = 0.44. Patterns in the two years are clearly different; total precipitation and distribution over the seasons explain why CFWone is reached earlier in 1994 than in 1993.

5. DISCUSSION OF SELECTED LAND-USE SYSTEMS



The essence of land evaluation is to match land use requirements with their corresponding land qualities. The latter characterize the land unit, described by its soil and terrain attributes and by its weather specifications. Land use requirements are specific to a particular land utilization type which is in turn described by the crop/variety grown and by all management attributes. The model used for land-use systems analysis is a comprehensive, deterministic crop production model, developed for dynamic analysis of the sufficiencies of selected land qualities under land use requirements as occur in rigidly defined production situations.

The biophysical production potential and the water-limited production potential are discussed. Specific land-use systems are examined with a view to their land unit specifications (weather data, soil salinity and capillary rise and drainage are discussed) and aspects of land-use (notably leaf area distribution, water requirements and crop growth reducing factors). The last part of this chapter presents conclusions and recommendations.

5.1. **Production potentials**

Biophysical production potential (PS1)

Recall that, at the highest hierarchical level in the model, crop production is analyzed for a system in which only the availability of solar radiation and the photosynthetic energy requirement at the prevailing temperature determine the production potential. Water and fertilizers, the main growth limiting factors, are assumed to be adequately available and growth reducing factors are controlled. Calculations of biophysical production potentials (PS1) require only crop and weather data. The processes that are successively considered in PS1 calculations are: i) production of assimilates, ii) allocation of these assimilates to the various plant organs; iii) loss of assimilates respired to maintain living material, and iv) conversion of remaining assimilates to structural plant matter.

Parameterization involved the following crop data: photosynthetic pathway (**C3C4$**); minimum air temperature for leaf development (**TLOW**); organ-specific relative maintenance respiration rates (**r(org)**); heat requirement for full crop physiological development (**TSUM**); threshold temperature for crop development (**T0**); heat requirement for full leaf development (**TLEAF**); extinction coefficient for visible light (**Ke**); partitioning fractions of assimilates to the various plant organs (**fr(org)**); specific leaf area function (**SLA**); and efficiency of assimilate conversion by plant-organ (**EC(org)**).

The land unit is characterized by one geo-referenced site (latitude, longitude, elevation). All weather data are daily data over at least the crop growth period. They include: maximum air temperature (**Tmax**); minimum air temperature (**Tmin**); relative air humidity (**RHA**); and daily sunny hours (**SunH**).

The following land unit data are calculated: day length (**DL**) calculated as a function of latitude and day in the year; extraterrestrial radiation (**EXTRA**) estimated from latitude and the day of year; atmospheric transmissivity (**TRANS**) estimated as a function of latitude, DL, SunH and RHA; 'photosynthetically active' radiation at canopy height (**PAR**) calculated from

EXTRA and TRANS. The daytime (**Tday**), nighttime (**Tnigth**) and equivalent daily temperature (**T24h**) are estimated by fitting of a coupled curve, sinusoidal at daytime and exponential at night.

Management data required to run PS1 scenarios define the date of crop emergence and the quantity of seed used per hectare.

To evaluate the variable values considered in the PS1 calculations, the following set of variables was analyzed: photosynthetically active radiation; average daily temperature; specific leaf area; maximum rate of assimilation; alternative assimilate partitioning patterns; and relative maintenance costs. These variables were input in a number of combinations, and the generated output was examined for length of plant growth (LPG), harvest (YIELD), harvest index (HI) and leaf area duration (LAD).

Under PS1 conditions, the length of plant growth (LPG) is only dependent on temperature and the crop's temperature requirements. This is different in scenarios examining the water-limited production potential (PS2) where drought affects LPG. It is generally true that yield reflects (the compounded effects of) all factors that influence crop growth and development but results show that different combinations may result in the same yield. The harvest index varies with all factors that influence dry matter accumulation by the various plant organs. The "leaf area duration" (LAD) is the most sensitive parameter. It is the result of processes that influence leaf maintenance: differences between the two years examined are not significant.

The results of the sensitivity analyses are used to calibrate the model. Set crop characteristics were matched with measured data: i) TSUM with observed crop duration; ii) r(org) with total dry matter; iii) TLEAF with maximum LAI, final LAI and LAD; iv) fr(org) with dry matter ratios.

The calculated biophysical production potential, differentiated by organ, as obtained with weather data for Coria del Rio 1994 (emergence date is 25 March) is shown in Fig. 5.1.

The yield (kg seed/ha, with an oil content of 43 %) is 70 % of the dry storage organ mass (the example shown in Fig. 5.1, suggests a potential yield around 4.2 tons seed/ha or 1.8 tons oil/ha). RAEA (Andalusian Agricultural Experimentation Network) has done extensive field research on sunflower. In the season 1991/93, trials with 46 varieties of sunflower at Posadas (Cordoba) gave an average yield of 3.8 ton/ha with an oil content of 51.7 %. For Florasol the figures are 4.1 and 53.4 % respectively (Junta de Andalucia, 1992). In the season 1993/94, trials with 40 varieties of sunflower at Palma del Rio (Cordoba) gave an average yield of 2.9 ton/ha with an oil content of 43.7 %. Florasol yielded 3.2 ton/ha with 41.3 % oil (Junta de Andalucia, 1994). These experiments were done under full irrigation (3 applications) and without fertilization (benefitting from nutrients carried over from the previous crop). Precipitation was 501 mm in 1991/92 and 342 mm in 1993/94. The differences between sites and sowing dates were caused by different weather conditions. The biophysical production potential could be realized under experimental conditions. The Agricultural Statistics of Andalusia show an average actual sunflower yield of 2.3 ton/ha under irrigation and 1.0 ton/ha for rain-fed sunflower (M.A.P.A., 1992). This suggests that sunflower yields in the region can still be doubled.

Conventional field experimentation does not explain the variation between varieties, sites and years. Differences between sites, years and sowing dates can be evaluated through dynamic modelling provided that available weather data are adequate. The few climatic variables required make the use of the program practical.

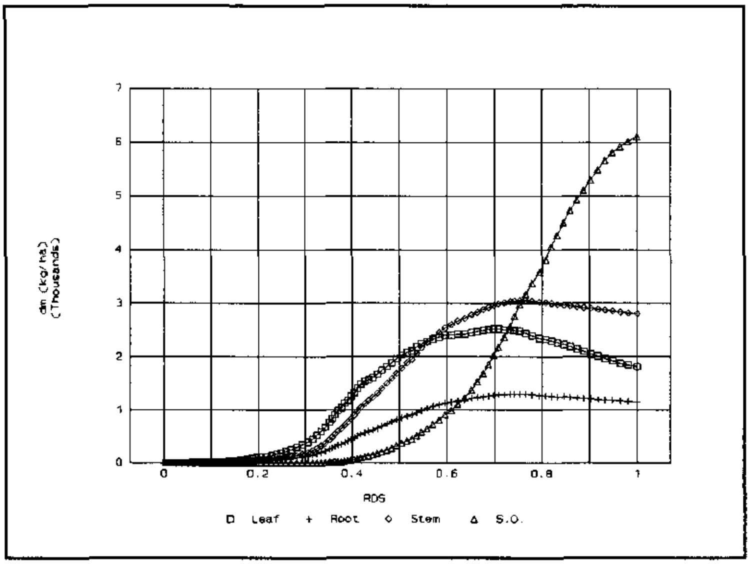


Fig. 5.1. Biophysical production potential of sunflower.

Leaf, Root, Stem and S.O. dry matter accumulation over the crop cycle.
RDS= 0 at emergence and RDS= 1 at physiological maturity.

Water-limited production potential (PS2)

At the second highest level in the model (PS2), the water-limited production potential is calculated considering the availability of water for uptake in addition to temperature and radiation. Plant nutrients are assumed to be adequately available and again growth reducing factors are assumed under control. Calculations of water-limited production potentials (PS2) require soil data and additional crop and weather data.

Shortage of water affects the rate of assimilation by a factor CFWATER, which expresses the relative sufficiency of water availability: CFWATER is the ratio of the actual transpiration rate (dictated by water supply) and the maximum transpiration rate (conditioned by water demand). The structure of the PS1 calculations is fully maintained in calculations at the PS2 level; only a water balance is added to the PS1-routine.

The rooted surface soil is treated as a one layer compartment; its upper boundary is the soil surface and its lower boundary is at an equivalent rooting depth that changes over the growing season. A water table may occur at a depth beyond the rooting depth. In terms of the water balance, the sources of water are precipitation, irrigation and capillary rise; evaporation, transpiration, surface runoff and deep percolation/drainage act as sinks. The rate of change of the volume fraction of moisture in the rooted surface compartment depends on all fluxes of water (vapour) through its two boundaries and on water extraction by roots for transpiration.

Essential (pedo)transfer functions in this water balance model are those defining: i) the moisture retention by the soil; ii) the hydraulic conductivity of the soil; iii) vertical flow of water in the soil; and iv) infiltration of water in the soil.

Parameterization produced the following soil data: total pore fraction (**SM0**); texture-specific constant for moisture retention (**GAM**); saturated hydraulic conductivity (**K0**); texture-specific geometry constant for hydraulic conductivity at low soil suction (**ALFA**); texture-specific empirical constant for hydraulic conductivity at high soil suction (**AK**); texture-specific suction boundary (**PSImax**); reference sorptivity (**S0**); and hydraulic permeability of the transmission zone (**Ktr**). Other soil characteristics determined included the field texture and the bulk density of the surface soil.

Additional crop data required for PS2 calculations are: initial rooting depth (**RDint**); maximum rooting depth (**RDm**); relative development stage at which root growth ceases (**RDSroot**); 'critical leaf water head' (**PSIleaf**); and mid-season crop coefficient (**TCM**).

Additionally required daily weather data include: precipitation (**PREC**) and wind speed (**Wind**) to compute the reference evapo(transpi)ration rates (**E0** and **ET0**).

Management data required to run PS2 scenarios define the state of the system (soil water relations) at the start of the growth cycle: matric suction of the root environment at the moment of crop emergence (**PSIint**); actual surface storage capacity (**ASSC**); actual storage of water on top of the soil at the time of emergence (**SSint**); depth of the phreatic level at the time of emergence (**ZTint**) with free or forced drainage; and **irrigation application** and **timing**.

Evaluating the sensitivities of variables considered in PS2 calculations, the following set of variables was examined: evapo(transpi)ration rates (E0 and ET0), hydraulic conductivity parameters (K0 and ALFA), soil moisture retention parameters (SM0 and GAM) and crop and soil parameters (PSIleaf, TCM and RDm). These variables were varied in a number of scenarios with a fixed irrigation schedule (application and timing), and the generated output was examined for seed production (Yield), leaf area duration (LAD), first day in the crop cycle with water stress (CFWone) and cumulative transpiration (sumTR).

It appeared that any water shortage affects yield and that this is primarily associated with the KPSI function used, and with the value of ALFA in particular. Accurate evapotranspiration data are very important. Yield is generally well correlated with LAD, CFWone and sumTR, but the relations are not linear. A very good correlation was found between LAD and LAImax, which could perhaps be used as a practical indicator of crop performance at field level. The CFWone-value which indicates the first day with water stress in the crop cycle is the result of interactions between all factors in the water balance. The most important factor affecting CFWone is again the value of ALFA. The cumulative actual transpiration (sumTR) represents total water uptake by the crop. The closer it is to the potential uptake, the better it correlates with yield. The differences observed between 1994 and 1993 are attributed to forcing variables, in particular to the amount and distribution of precipitation.

The results of the sensitivity analyses are used to judge the adequacy of the crop and soil parameter values used. This was done by correlating with measured field data: i) KPSI with soil moisture content; ii) the CFWone value with irrigation data; and iii) the Yield with maximum LAI and LAD. The CFWone value was used to judge the correctness of fitting. This calibration process led to a proposed "new" KPSI function described only by K0 and ALFA (eqn. 4.76). The new ALFA value was set at 0.18 cm^{-2} after matching the CFWone value with the date at which the first irrigation was applied.

The next two figures show that cumulative dry masses calculated for PS1 and PS2 scenarios, the latter with different water regimes: a 'Wet' treatment (PS2-W); a 'Half' treatment (PS2-H); and a 'Dry' treatment (PS2-D). Each figure was calculated with weather data from Coria del Rio as recorded in 1993 (emergence date is DOY 96) and in 1994 (emergence date is DOY 85).

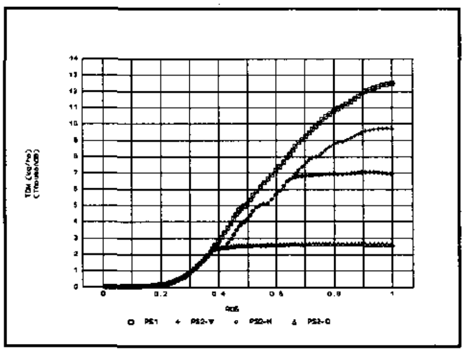


Fig. 5.2. PS1 and PS2 scenarios with different water regimes, Coria del Rio 1993.

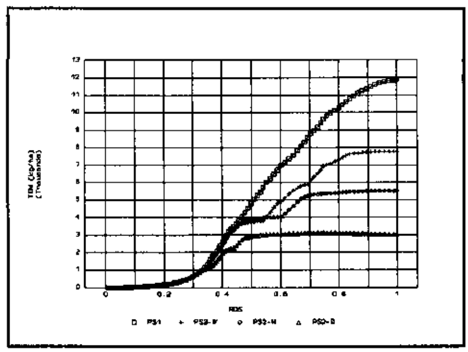


Fig. 5.3. PS1 and PS2 scenarios with different water regimes, Coria del Rio 1994.

Historic weather data can be used to evaluate the long-term success of a land-use system, which is important for risk assessment. Fig. 5.4 shows yield values calculated for the period between 1972 and 1994. The results were generated for emergence on day 85 (26 of March) with a sowing density of 5 $kg.ha^{-1}$ and an initial soil suction of 1000 hPa. The curve 'Yield-PS1' represents the yield component of the biophysical production potential (PS1) over the years. Its variation reflects the effects of changing environmental conditions on crop production. Calculated yield potentials varied between 4844 and 3948 $kg.ha^{-1}$. The curve 'Yield-PS2' represents the yield component of the water-limited (rainfed) production potential (PS2). Water scarcity reduced yields to less than 800 $kg.ha^{-1}$. Water is the main limiting crop production factor in Andalusia.

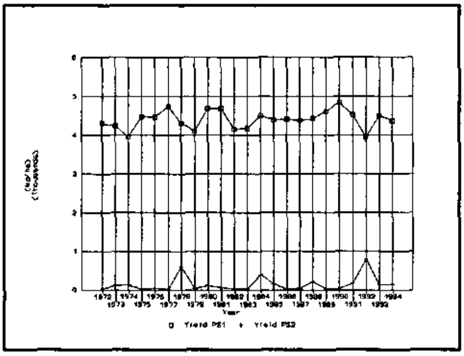


Fig. 5.4. Calculated potential sunflower yields for PS1 and PS2 production situations in Coria del Rio.

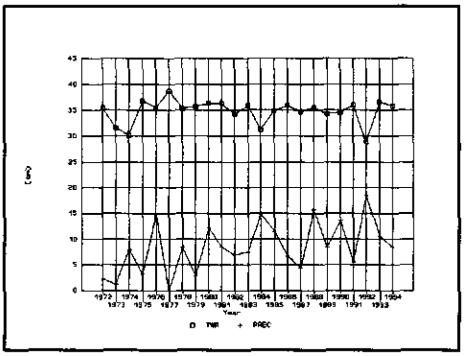


Fig. 5.5. Precipitation (PREC) and total water needs (TWR) for sunflower under PS1 conditions.

Fig. 5.4 shows scenarios run from a fixed emergence date: better results can be generated by using a higher initial soil moisture content.In practice, farmers wait for rains that create a desired soil moisture content. Fig. 5.5. shows why yields are so low under rainfed farming: the precipitation during the growing season cannot cover the water requirements for optimal crop cultivation. More results generated for these two production situations are shown in Table 5.1.

Table 5.1. Some indicator values of crop performance calculated for production situations PS1 and PS2 at Coria del Rio, for the years 1972 to 1994.

	PS1				PS2			
Year	LPG	LAD	LAImax	LAIf	LAD	LAImax	CFWone	CFWATER
1972	121	299	5.6	0.0	57	1.7	48	0.58
1973	118	253	5.0	0.3	55	1.7	51	0.74
1974	115	229	4.7	0.3	44	1.5	53	0.75
1975	119	258	4.9	0.2	45	1.4	50	0.57
1976	112	219	4.8	0.5	55	2.0	57	0.70
1977	119	247	4.6	0.4	43	1.3	49	0.58
1978	117	213	4.0	0.5	48	1.2	51	0.77
1979	110	217	4.5	0.6	38	1.3	49	0.64
1980	108	183	3.8	0.9	49	1.6	53	0.69
1981	110	197	4.3	0.7	42	1.3	52	0.70
1982	106	167	3.8	0.9	36	1.3	51	0.66
1983	114	201	4.2	0.4	49	1.6	55	0.67
1984	115	186	3.6	0.9	64	1.6	57	0.79
1985	112	203	4.1	0.8	67	2.0	58	0.77
1986	111	223	4.9	0.5	33	1.2	49	0.61
1987	105	190	4.1	1.0	42	1.4	47	0.60
1988	108	207	4.3	0.9	62	2.0	54	0.81
1989	104	196	4.4	0.9	41	1.4	48	0.63
1990	106	199	4.3	1.0	39	1.4	49	0.62
1991	106	216	4.7	0.7	44	1.4	48	0.65
1992	104	180	3.8	0.6	59	1.6	47	0.79
1993	112	230	4.7	0.5	85	2.6	57	0.76
1994	106	206	4.3	0.6	74	1.3	46	0.67
Year	LPG	LAD	LAImax	LAIf	LAD	LAImax	CFWone	CFWATER
maximum:	121	299	5.6	1.0	85	2.6	58	0.81
minimum	104	167	3.6	0.0	33	1.2	46	0.57

```
where
LPG       is length of plant growth (d).
LAD       is leaf area duration (m².d).
LAImax    is maximum LAI in the crop cycle (m².m⁻²).
LAIf      is LAI at maturity (m².m⁻²).
CFWone    is first day of water shortage (d).
CFWATER   is overall water sufficiency (-).
```

The variation of LPG, LAD and LAImax values in Table 5.1 reflects the changing environmental conditions; temperature and radiation at PS1, and (additionally) water availability at PS2. The average yield under PS1 was 4407 $kg.ha^{-1}$ (mean of 23 runs); averaging the weather data for the same period results in a generated yield estimate of 4492 $kg.ha^{-1}$. Average values for production and yield can only be used as indicators and for comparison; and only for PS1 production situations.

The CFWATER values in Table 5.1. denote overall water sufficiencies. Their minimum value of 0.57 corresponds to a (near) crop failure; the yield at the maximum CFWATER value of 0.81, is far less than the yield calculated for PS1. The use of CFWATER for single-factor analysis can be misleading.

The CFWone value is a good indicator for planning irrigation scheduling. Irrigation scenarios will normally try to push the CFWone value towards the end of the cropping season, through a variety of combinations of applications and timing.

5.2. Aspects of land

Weather specifications

Weather data of Coria del Rio (latitude 37.28 °N, longitude 6.09 °E, altitude 39 m) are available for 1971 to 1995. Original data are stored in DBase format and were made available by the Department of Sustainable Soil-Plant-Atmosphere System, Institute for Natural Resources and Agrobiology of Seville (IRNAS).

These data include daily values of maximum air temperature (Tmax in °C); minimum air temperature (Tmin in °C); precipitation (PREC in mm); relative air humidity (RHA in %) at 1, 7, 13 and 18 hours; Piche evaporation (E0 in mm); sun hours (SunH in h) and wind speed (Wind in $km.d^{-1}$). The data are recorded as integers, which is disturbing in the case of SunH (where the error is half an hour in a maximum number of 14 hours).

The original data base shows several missing single values. Some of the data are obviously wrong (RHA > 100, SunH > DL, Tmin > Tmax, and alike); others are typing errors. Missing data account for less than 2 % of the full data set. Missing single values were patched by estimating most probable values. Missing data that cover a longer period of time will be dealt with hereafter.

The most disturbing data gaps are the following:

1971 - data only available from DOY 121 on.
1978 - no RHA from DOY 151 on.
1981 - no RHA from DOY 1 to 243.
1982 - no RHA (at 1, 13 and 18 H) from DOY 1 to 31.
1983 - no RHA (at 1, 13 and 18 H) from DOY 335 to 365.
1985 - no Wind from DOY 335 to 365.
1992 - no Wind from DOY 245 to 274 and from 305 to 335.
1993 - no Wind from DOY 83 to 113.
1995 - data until DOY 212.

Some characteristic values, after correction of erroneous or single missing values, are shown in Table 5.2.

Table 5.2. Climate characteristics of Coria del Rio, recorded between 1971 and 1995.

Year	PREC	Extremes		Tavg	RHA	SunH	E0 (mm)	W (km/d)
	sum	Tmax	Tmin	avg	avg	sum	sum	avg
1971	230	40	-2	18.1	0.61	2076	1086	30.8
1972	700	40	0	16.1	0.72	3030	1226	32.8
1973	256	40	-1	16.5	0.61	3061	1398	28.8
1974	235	41	-1	16.8	0.64	2940	1332	25.2
1975	280	44	0	17.0	0.62	2948	988	91.0
1976	756	42	-6	16.9	0.65	2938	930	107.4
1977	598	38	-2	17.2	0.64	2817	881	114.4
1978	378	43	-2	18.1	0.68	2748	1106	131.4
1979	525	41	-7	18.1	0.65	2654	1181	134.0
1980	226	40	-5	18.2	0.63	2881	1486	130.3
1981	260	42	-5	17.9	0.58	2922	1539	129.3
1982	374	43	1	18.1	0.58	2786	1190	127.6
1983	394	40	-6	18.4	0.58	2599	1250	127.8
1984	484	40	-1	17.6	0.76	2592	1204	123.9
1985	523	42	-2	18.4	0.68	2761	1285	132.7
1986	371	40	0	18.0	0.70	2868	1276	118.5
1987	839	40	0	18.6	0.66	2774	1249	122.4
1988	501	43	1	19.0	0.62	3104	1282	117.0
1989	801	43	2	19.7	0.73	3055	1331	124.2
1990	412	40	1	19.0	0.76	3146	1275	109.4
1991	487	43	0	18.7	0.74	3216	1212	98.7
1992	397	42	-3	18.2	0.75	3126	1147	96.3
1993	346	42	-5	17.3	0.68	3102	1296	119.1
1994	299	44	-2	18.5	0.61	3201	1388	121.7
1995	135	46	-1	18.6	0.63	1921	839	121.9
maximum :	839	46	2	19.7	0.76	3216	1539	134.0
minimum :	135	38	-7	16.1	0.58	1921	839	25.2
average :	432			18.0	0.66	2851	1215	104.7
std.dev.:	186			0.8	0.06	307	169	35
c.v. (%):	43			5	9	11	14	33

Table 5.2 shows that temperature, relative air humidity, sun hours and wind speed vary by less than 25 % over the 25 years on record. Precipitation varies greatly between years.

<u>Temperature data</u>

Individual records of this 25 year period show the following extremes:

```
maximum : Tmax = 46;  Tmin = 28
minimum : Tmax =  7;  Tmin = -7
```

The first incidence of frost occurred on December 5 and the last on March 2.

Maximum air temperatures over 35 °C occurred from May 13 to October 10. On average,such temperatures must be expected between July 15 and August 18. Daily maximum temperatures in excess of 40 °C may occur between June 6 till October 10.

The average daily temperature amplitude ranges from 10 °C in winter to 16 °C in summer. The variation of Tmax is greater than the variation of Tmin in summer; the opposite happens in winter.

Averaging all daily temperature values over the 25 years period produces Table 5.3:

Table 5.3. Average values and standard deviations of daily temperatures in Coria del Rio from 1971 to 1995.

Stats	Tmax	std	Tmin	std
maximum :	35.8	5.6	18.5	5.0
minimum :	14.8	1.8	4.7	1.8
average :	24.3	3.3	11.4	3.2
std.dev.:	6.5	0.8	4.2	0.6
sum :	8902		4184	

where the standard deviation, in the column, shows the variation between the same days of year during the 25 years period, and in the row, the variation between the days within the average year.

These average values show a pattern that allows to simulate a seasonal course of temperature on the basis of real monthly data. Table 5.4 shows the result of such a simulation exercise.

Table 5.4. Simulated maximum and minimum air temperatures.

Stats	Tmax	Tmin
maximum :	33.6	16.4
minimum :	15.0	6.4
average :	24.3	11.4
std.dev.:	6.6	3.6
sum :	8870	4169

The results in Table 5.4 accord with those in Table 5.3. A good impression of the adequacy of the simulation is given by Fig. 5.6.

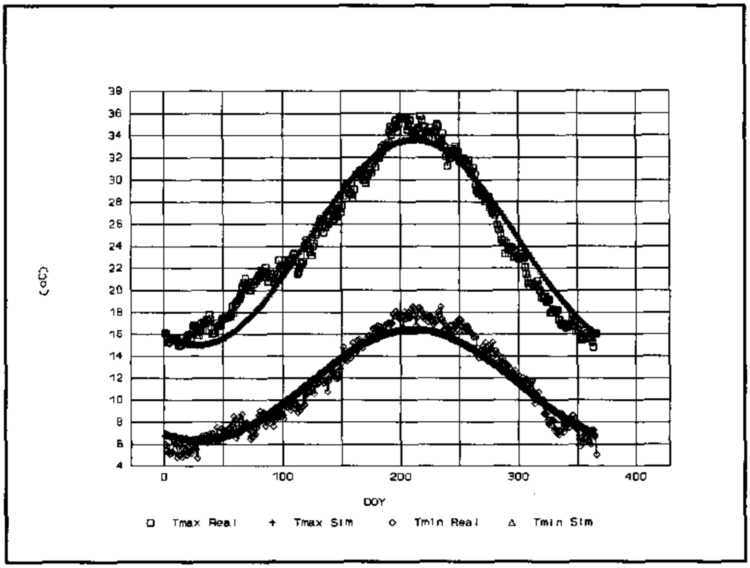


Fig. 5.6. Measured ('Tmax Real' and 'Tmin Real') and simulated ('Tmax Sim' and 'Tmin Sim') daily mean air temperatures.

The correlation coefficients for monthly and daily maximum air temperature are 0.96 and 0.95 respectively, and 0.95 and 0.93 respectively for monthly and daily minimum air temperature. Because of this good correlation the procedure was used to estimate missing values.

Daily temperature (T in °C) is described by a sinusoidal curve of the type (Goudriaan, 1993):

```
T = a + b * Sin(Alfa)                                                   (5.1)
```

By linear regression it was found that the coefficients in this equation could be defined for the area of Coria del Rio as:

```
a      the reference level temperature.
b      the degree of bending of the curve.
Alfa   the peak of the curve (in radians).
```

From this general equation, two others are derived that describe Tmax and Tmin. The daily maximum temperature is described by:

```
Tmax = AAmax + BBmax * Sin(Alfa1)                                       (5.2)

where
AAmax  is average maximum year temperature.
BBmax  is half of maximum temperature amplitude.
Alfa1  is peak maximum temperature in the year.
```

Similarly, daily minimum temperature is described by:

```
Tmin = AAmin + BBmin * Sin(Alfa2)                                       (5.3)
```

```
where
AAmin  is average minimum year temperature.
BBmin  is half of maximum temperature amplitude.
Alfa2  is peak minimum temperature in the year.
```

In Quick Basic code, the relations are written as:

```
AAmax = Sum_TmaxReal(Month) / 12
BBmax = (Max_TmaxReal - Min_TmaxReal) / 2
Alfa1 = (2 * 180 * (DOY - TTmax) / 365)
TTmax = ABS(Month_of_Max_TmaxReal - Month_of_Min_TmaxReal) * 15 + 30

AAmin = Sum_TminReal(Month) / 12
BBmin = (Max_TminReal - Min_TminReal) / 2
Alfa2 = (2 * 180 * (DOY - TTmin) / 365) * RAD
TTmin = ABS(Month_of_Max_TminReal - Month_of_Min_TminReal) * 15 + 60

where
TmaxReal(Month)   is measured monthly maximum temperature.
TminReal(Month)   is measured monthly minimum temperature.
DOY               is day number of the year (1st of January = 1).
Rad               is conversion into radians (Rad = π / 180).
```

RHA data

Relative air humidity was measured at 1.00 hours (RHA01), at 7.00 hours (RHA07), at 13.00 hours (RHA13) and at 18.00 hours (RHA18). The average values are shown in the next figure.

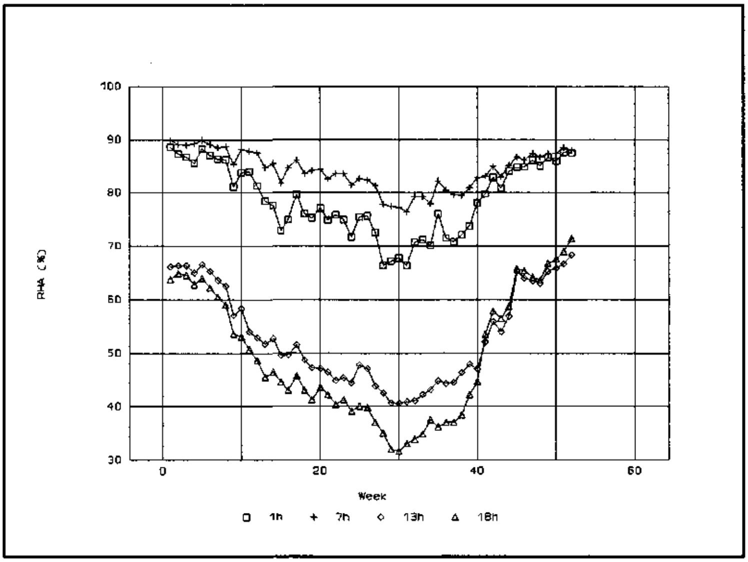


Fig. 5.7. Average values of RHA measured at different hours.

Linear regression tests were done to check whether missing RHA data could be approximated/patched by linear interpolation. The results are shown in Table 5.5.

Table 5.5. Linear regression coefficients for RHA data.

Regression	Constant	X coefficient	R squared
1. RHA01 vs AVG	18.1	0.8947	0.93
2. RHA07 vs AVG	50.8	0.4932	0.83
3. RHA13 vs AVG	-30.6	1.2365	0.96
4. RHA18 vs AVG	-58.6	2.8870	0.94
5. RHA07+RHA13 vs AVG	10.1	0.8649	0.98
6. RHA07+RHA13+RHA18 vs AVG	-23.7	1.2416	0.99
7. RHA07 vs RHA1+RHA13+RHA18	61.4	0.3766	0.75
8. AVG vs Tavg	90.8	-1.2828	0.85

Most of the missing relative air humidity data are data of RHA01, RHA13 or RHA18; data for 7.00 hours are available. In some cases the entire set was missing. If only RHA07 data are available, regression 2 can be used. If the complete data set is missing, regression 8 can be used. Table 5.5 shows that measurements at 18.00 hours (regression 6) and at 1.00 hours (regression 5) could be dropped. One intermediate measurement between 7 o'clock and 13 o'clock would suffice to characterize daily relative air humidity.

Fig. 5.8 is constructed using regression equation 8.

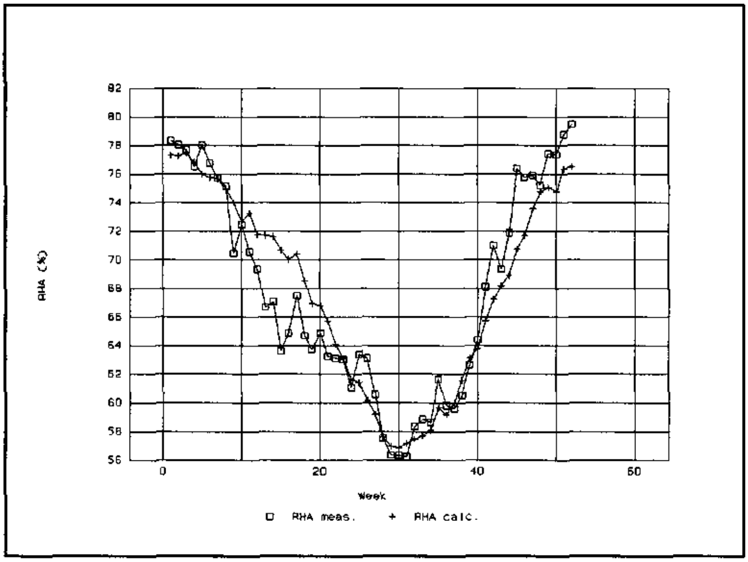


Fig. 5.8. Average daily relative air humidity, measured ('RHA meas.') and simulated ('RHA calc.') using regression equation 8 (Table 5.5).

Sun hours

From 1972 to 1974, observed extreme yearly values were between 3216 hours (or 8.8 hour.day^{-1}) and 2592 hours (or 7.1 hour.day^{-1}). The average daily SunH values over the year are depicted in Fig. 5.9.

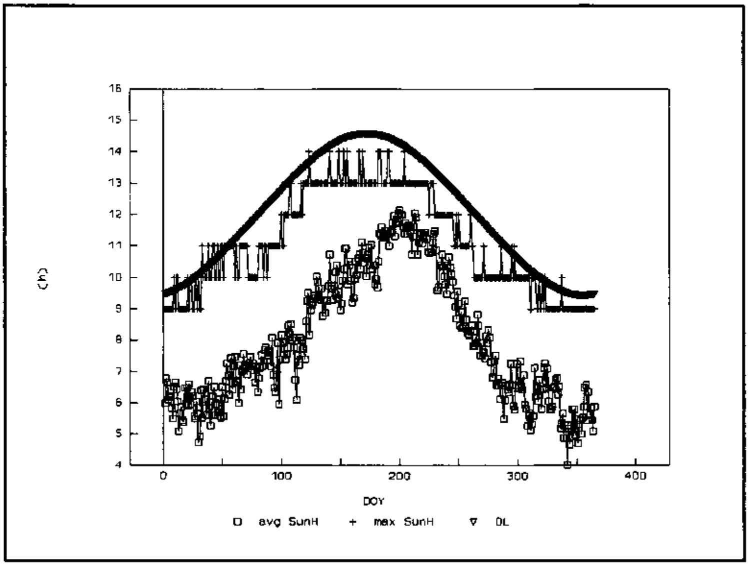


Fig. 5.9. Sun hours (average 'avg SunH' and maximum 'max SunH') and day length ('DL') of Coria del Rio.

The average annual sum of sun hours was 2920 hour.year^{-1}. This corresponds with a theoretical average value of 8.0 hour.day^{-1}. The maximum value was 12.1 hour.day^{-1} and the minimum 4.0 hour.day^{-1}. The standard deviation is 2.1 hour.day^{-1}, which implies a coefficient of variation of 26 %.

Precipitation

The distribution of rainfall is shown in Table 5.6, where rainfall data are grouped by number of events and maximum and minimum amounts of a single shower. The column 'sum' presents the annual total.

Table 5.6. Rainfall data.

Year	Events number	Rainfall records (mm) max	min	sum	Year	Events number	Rainfall records (mm) max	min	sum
1972	74	44	1	700	1973	36	37	1	256
1974	40	28	1	235	1975	24	38	1	280
1976	64	60	1	756	1977	49	43	1	598
1978	43	39	1	378	1979	58	61	1	525
1980	29	27	1	226	1981	36	38	1	260
1982	37	87	1	374	1983	39	62	1	394
1984	52	47	1	484	1985	52	33	1	523
1986	34	50	1	371	1987	57	47	1	839
1988	49	55	2	501	1989	59	53	1	801
1990	39	35	1	412	1991	34	44	1	487
1992	35	33	2	397	1993	43	32	1	346
1994	34	39	1	299					
Average	44	45	1	454					

The annual fluctuation of precipitation between 1972 and 1994 is depicted in Fig. 5.10.

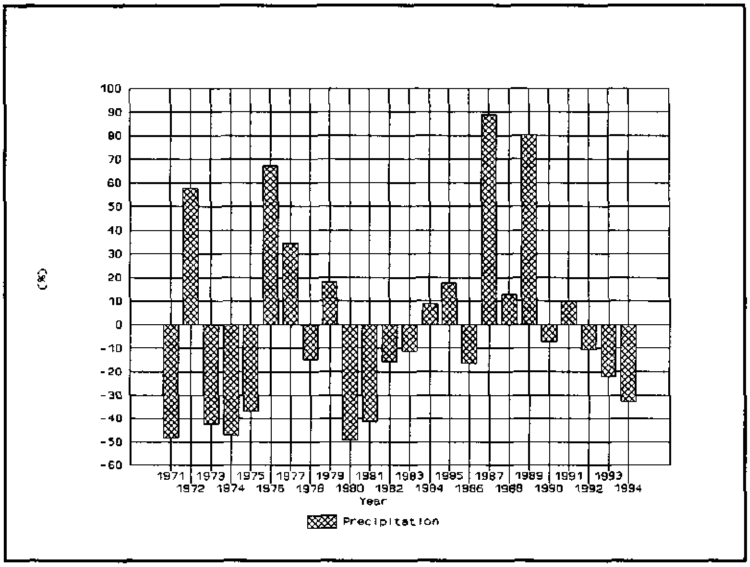


Fig. 5.10. Deviation of annual precipitation from the long-term average in Coria del Rio from 1972 to 1994.

The intensity of single showers is plotted versus the frequency of occurrence of that amount in Fig. 5.11. The basic data comprised 1017 precipitation events recorded between 1972 and 1994.

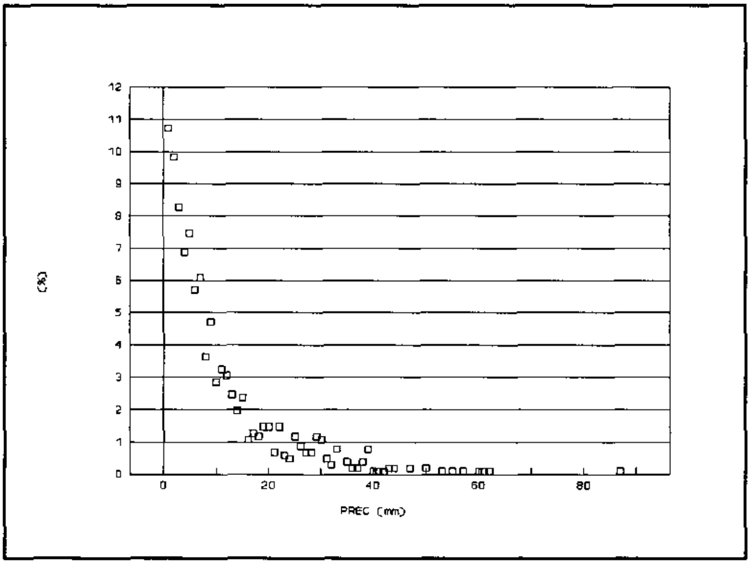


Fig. 5.11. Intensity distribution of single showers in Coria del Rio, 1972-1994.

Arranging these frequency data in interval classes yields Table 5.7.

Table 5.7. Relative distribution of rainfall events.

Precipitation	%	cumulative
<= 5 mm	43.2	43.2
5 to <=10 mm	23.0	66.2
10 to <=15 mm	13.1	79.3
15 to <=20 mm	6.5	85.7
20 to <=25 mm	4.4	90.2
25 to <=30 mm	4.5	94.7
30 to <=35 mm	2.0	96.7
35 to <=40 mm	1.7	98.3
40 to <=50 mm	1.0	99.3
> 50 mm	0.7	100.0

Fig. 5.11 and Table 5.7 show the distribution of individual showers in Coria del Rio. The relative distribution over the year is shown in Fig. 5.12. The data shown are averaged for weekly periods.

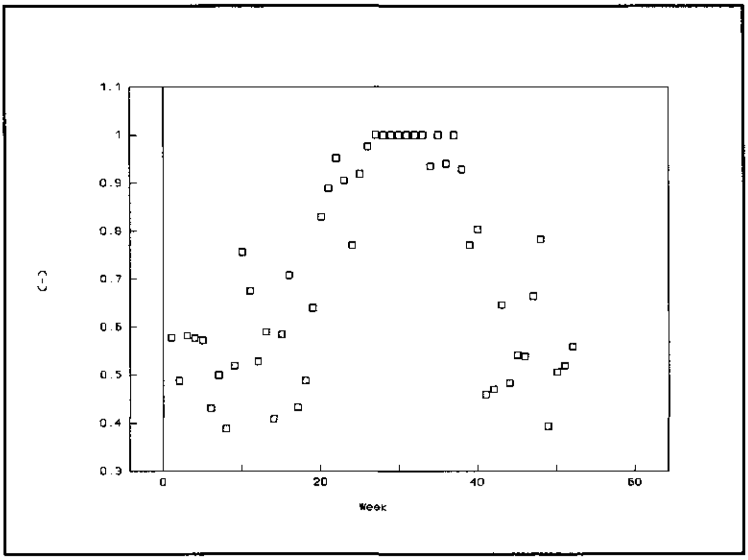


Fig. 5.12. Relative distribution of the ratio of maximum single shower over total precipitation.

Fig. 5.12 shows that it is very probable that a single shower supplies most of the precipitation in weeks 20 (May 14) to 40 (October 1). The period has also the lowest probability of rain events. Average weekly precipitation over the year is shown in Fig. 5.13.

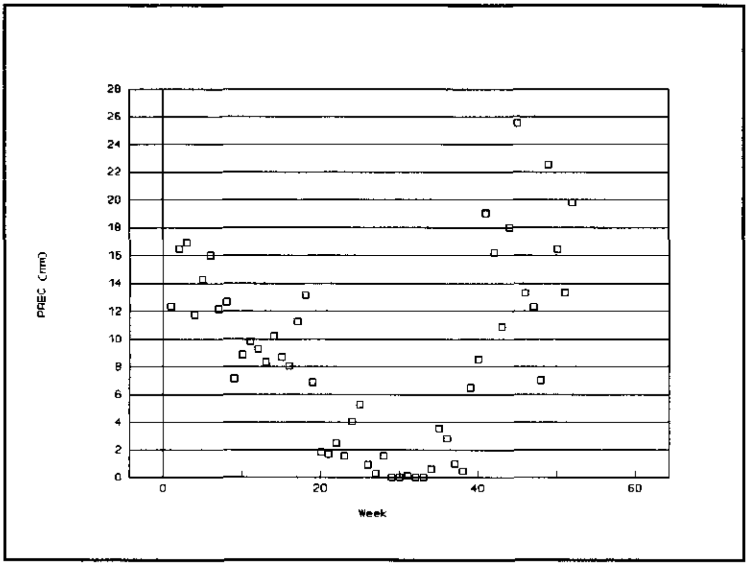


Fig. 5.13. Average weekly precipitation over the year.

The aridity index shows to what extent precipitation meets the evaporative demand of the atmosphere; the 'aridity index' is the ratio of total precipitation over total potential evaporation.

Table 5.8. Aridity index.

Year	PREC (mm)	EO (mm)	Aridity Index
1972	700	1226	0.57
1973	256	1398	0.18
1974	235	1332	0.18
1975	280	988	0.28
1976	756	930	0.81
1977	598	881	0.68
1978	378	1106	0.34
1979	525	1181	0.44
1980	226	1486	0.15
1981	260	1539	0.17
1982	374	1190	0.31
1983	394	1250	0.32
1984	484	1204	0.40
1985	523	1285	0.41
1986	371	1276	0.29
1987	839	1249	0.67
1988	501	1282	0.39
1989	801	1331	0.60
1990	412	1275	0.32
1991	487	1212	0.40
1992	397	1147	0.35
1993	346	1296	0.27
1994	299	1388	0.22

To distinguish 'dry' from 'wet' years, it is suggested to use an aridity index >= 0.75 for wet years and < = 0.33 for dry years (De la Rosa, 1993).

Averaging E0 and PREC over the year yields Table 5.9.

Table 5.9. Average annual precipitation and evaporation (mm).

Month	E0	PREC	exc	def
1	49	63	14	
2	59	54		5
3	89	36		52
4	98	41		57
5	127	26		101
6	143	13		130
7	181	2		179
8	176	5		171
9	129	10		119
10	88	56		32
11	60	68	7	
12	50	74	24	
sum:	1249	449	46	846

where 'exc' is precipitation surplus (PREC-E0) and 'def' is deficit.

Wind data

Wind speed data are needed for calculations of evapotranspiration. Daily wind speed data show a maximum of 1.66 $m.s^{-1}$ in summer and a minimum of 0.79 $m.s^{-1}$ in winter.

Soil salinity

In many agricultural lands, especially in arid zones, soil salinity builds up in the root zone, e.g. because of input of salts with irrigation water or capillary rise. The present work tests a methodology for quantifying soil salinity within dynamic simulation of crop growth.

The water balance keeps track of all water fluxes in or out of the rooted surface compartment (precipitation, irrigation, evaporation, transpiration, surface runoff and capillary rise or deep, percolation/drainage). The effects of salinity are made visible by accounting for the salt load of each water flux. Osmotic pressure increases the total soil moisture potential and affects the uptake of water for transpiration and hence the rates of assimilation and growth/production.

The electrical conductivity of the groundwater (EC_w, in $dS.m^{-1}$), of the irrigation water (EC_i) and the initial electrical conductivity of the soil saturation extract (EC_e) are model inputs. The state variable which expresses the salinity of the system is the electrical conductivity of the actual soil solution (EC(Day)).

Uptake of water by the root system is conditioned by total stress (PSItot), composed of the matric potential (PSI) and the osmotic pressure (OP). The relation between OP (in atm) and shift in freezing point (DELFRPNT, in °C) caused by dissolved salts is given by Thorne and Peterson (1954) as:

```
OP = 12.06 * DELFRPNT - 0.21 * DELFRPNT²                          (5.4)
```

The Handbook of Chemistry and Physics (Weast, 1975) gives the osmotic parameters and electrical conductivities of aqueous solutions of sodium chloride. The following equation was constructed (r^2=0.99994):

```
EC = 28.26 * DELFRPNT - 2.33 * DELFRPNT²                          (5.5)
```

Combining equations (1) and (2), the relation between OP (in cm) and EC is found:

```
OP = 463 * EC                                                     (5.6)
```

The approximate relation between EC and salt concentration (Co in $g.l^{-1}$) used reads:

```
EC = 1.464 * Co                                                   (5.7)
```

The total quantity of salt in the rooting zone (SOILSalt) is composed of salt in the original material (SaltSURFACE) minus salt leached (SaltPERCED) plus salt added with root growth (SaltDEEP), irrigation (SaltIRRIG) and capillary rise (SaltRISEN):

```
SOILSalt = SaltSURFACE + SaltDEEP + SaltIRRIG - SaltPERCED + SaltRISEN(5.8)
```

Leaching water (D) is assumed to have the salt content of the soil moisture. The quantity of salt leached, per hectare and per interval (Dt), is approximately equal to:

```
SaltPERCED = D * Dt * (EC(Day) / 1.464) * 100                     (5.9)

where 100 is a factor to satisfy units.
```

Likewise, salt influx with capillary rise (CR), per hectare and per interval (Dt) amounts to:

```
SaltRISEN = CR * Dt * (EC_w / 1.464) * 100                        (5.10)
```

Not all irrigation water enters the soil; part may be discharged as surface runoff. Salt added with effective irrigation (IE) water inputs salts:

```
SaltIRRIG = IE * Dt * (EC_i / 1.464) * 100                        (5.11)
```

Salt already present in the soil (SaltSURFACE) is assumed to be dissolved in the soil moisture stored in the (last calculated) rooted surface compartment (oldRD in cm):

```
SaltSURFACE = (SMPSI / BD) * oldRD * (EC(Day) / 1.464) * 100      (5.12)

where
SMPSI is soil moisture content (cm³.cm⁻³)
BD    is soil bulk density (g.cm⁻³)
```

Salt added with root growth (SaltDEEP) amounts to:

```
SaltDEEP = (SMPSI / BD) * (RD - oldRD) * (EC(Day - 1) / 1.464) * 10(5.13)
```

The total quantity of salt in the rooted surface compartment can be calculated (SOILSalt; equation (5.8)) and the state variable EC can be adjusted for the next time interval:

```
EC(Day) = (SOILSalt / ((SMPSI / BD) * RD * 100)) * 1.464          (5.14)
```

Bulk density (BD) is used to convert volumetric water content (SMPSI) to gravimetric water content. It may be calculated from the total soil porosity (SM0 in $cm^3.cm^{-3}$, provided in the soil file):

```
BD = 2.6 * (1 - SM0)                                              (5.15)
```

Yield calculations

Groundwater is the water source for irrigation in the study area. Its electrical conductivity (EC_w) varies between 2.11 and 1.74 $dS.m^{-1}$. The electric conductivity of the soil saturation extract (EC_e) varied between 0.17 and 0.24 $dS.m^{-1}$.

Table 5.10 shows results generated for scenarios with different irrigation regimes. The electric conductivity of irrigation water (EC_i) is set to the same value as that of groundwater ($EC_i = EC_w = 2.0$ $dS.m^{-1}$) and the initial electric conductivity of the soil saturation extract $EC_e = 0.20$ $dS.m^{-1}$. All scenarios were run for weather data of Coria del Rio, 1993; the matric suction at emergence (on day 96) was 1000 cm, and sowing density amounted to 5 $kg.ha^{-1}$.

Table 5.10. Salinity risks under different irrigation regimes.

TDM	7061	6083	7582	8852	8336	9083	9633
SO	1901	1839	2826	2582	2672	2606	3228
CFWone	63	57	54	67	61	69	67
EC	3.99	3.63	4.46	8.29	5.85	5.36	4.28
EC_e	1.14	0.96	1.19	2.32	1.58	2.20	1.14
SMPSI	0.13	0.12	0.13	0.13	0.13	0.19	0.13
Irrigation schedule (Day and applic. (cm))	50 5 55 5 60 5 65 5 70 5 75 5 80 5 85 5	50 3 55 3 60 3 65 3 70 3 75 3 80 3 85 3	50 2 55 2 60 3 65 4 70 5 75 6 80 5 85 4	40 5 50 5 60 8 70 10 80 8 90 4	40 5 50 7 60 10 70 10 80 10 90 8	40 5 50 7 60 10 70 10 80 10 90 8	50 5 57 7 64 10 71 10 78 10 85 8
number amount (cm)	8 40	8 24	8 22	6 40	6 50	6 50	6 50
SO/TDM	0.27	0.30	0.37	0.29	0.32	0.29	0.34
TDM/amount	1.8	2.5	3.4	2.2	1.7	1.8	1.9
TDM	10100	10120	10065	9404	10029	8845	6264
SO	4390	4464	4538	3228	3464	2553	996
CFWone	54	54	54	54	54	54	54
EC	6.10	8.29	8.67	6.44	4.60	3.53	3.77
EC_e	3.41	3.78	2.43	1.76	1.23	0.93	2.11
SMPSI	0.26	0.21	0.13	0.13	0.13	0.12	0.26
Irrigation schedule (Day and applic. (cm))	55 10 65 10 75 10 85 10 95 10	55 8 65 12 75 12 85 12 95 6	60 10 70 12 80 12 90 6	55 10 65 12 75 12 85 6	55 10 70 10 85 10	55 10 75 10	55 10 85 10
number amount (cm)	5 50	5 50	4 40	4 40	3 30	2 20	2 20
SO/TDM	0.43	0.44	0.45	0.34	0.35	0.29	0.16
TDM/amount	2.0	2.0	2.5	2.4	3.3	4.4	3.1

```
where:
TDM      is total dry matter (kg.ha-1).
SO       is storage organ dry matter (kg.ha-1).
CFWone   is first day in the crop cycle with water shortage (Day).
EC, ECe and SMPSI values at crop maturity.

Irrigation schedule is defined by the dates and amounts of single
applications (Day and application); and by the number of applications and
the total amount given (number, amount).
```

Row 'TDM/amount' in Table 5.10 can be seen as an expression of water use efficiency. Its unit is in $kg.m^{-3}$. The general trend is that water use efficiency decreases with increasing rates of water application (see water use efficiencies at the same amounts of application).

Irrigation strategies can be tested for an unlimited number of scenarios. In Table 5.10, row 'CFWone' indicates the first day in the crop cycle at which the crop experiences water shortage under the specified irrigation schedule. Row 'SMPSI' gives the soil moisture content at crop maturity. These two figures can be combined with a target level of production and water use efficiency to define a specific irrigation schedule. Runs with single applications of 13 cm of water caused crop failure because of extended periods of soil saturation.

Similarly, leaching requirements can be tested by defining a permissible level of soil salinity and analysing different irrigation schedules, landuses (different crops and/or fallow) or depths of the groundwater. For each scenario a different leaching requirement is generated.

In F.A.O. 29 (Ayers and Westcot, 1985), sunflower is stated to be moderately sensitive to soil salinity. This relative tolerance is indicated by its threshold salinity level, between conductivity values of 1.3 and 3.0 $dS.m^{-1}$ in the saturation extract.

Note that the conductivity of the saturation extract (EC_e) is defined as the electric conductivity of a saturated soil paste at 25 °C. The real soil water content varies strongly between sites and between years. Table 5.10 suggests that the actual soil salinity level (EC) may be 2 to 4 times greater than EC_e, and could rise even further if the soil moisture content becomes less. It is conceptually better to relate yield depression by excess electrolytes in the soil solution not only to EC_e but also to soil moisture regime. In this study EC is expressed as the electric conductivity at actual soil moisture content:

$$EC = SMO / SMPSI * EC_e \tag{5.16}$$

Table 5.11 shows the results generated for a scenario with 40 cm water (same quality as before) applied in 6 doses (5 cm on day 40, 5 cm on day 50, 8 cm on day 60, 10 cm on day 70, 8 cm on day 80 and 4 cm on day 90 in the crop cycle). Emergence is on day 96 in the year, seed density is 5 $kg.ha^{-1}$. The results are generated with weather data of Coria del Rio, 1992 and 1993.

Table 5.11. Salinity risks as influenced by weather specifications.

Year	1972	1975	1978	1981	1984	1987	1990	1993
tdm	5732	7549	7694	8752	8439	10177	8603	8852
so	307	1569	1850	3445	2878	4721	3402	2582
CFWone	64	72	75	64	67	60	57	67
EC	4.14	5.99	6.11	8.82	5.66	10.91	9.18	8.29
EC_t	1.72	1.78	1.66	2.98	1.53	4.49	3.84	2.32
SMPSI	0.19	0.14	0.13	0.16	0.13	0.19	0.20	0.13
PREC	2.2	0.0	8.0	3.7	13.7	5.7	10.0	10.5
so/tdm	0.05	0.21	0.24	0.39	0.34	0.47	0.40	0.29
SO/TDM	0.47	0.50	0.52	0.53	0.54	0.52	0.53	0.51
so/SO	0.05	0.24	0.31	0.54	0.47	0.81	0.52	0.40
WUE	1.4	1.9	1.9	2.2	2.1	2.5	2.2	2.2

where
PREC is amount of precipitation during the growing season (cm).
so/tdm is ratio of 'so' and 'tdm' (-).
SO/TDM is 'so/tdm' but for PS1 (-).
so/SO is ratio of actual and potential storage organ dry masses (-).
WUE is water use efficiency; ratio of 'tdm' and water application, in all cases 4000 $m^3.ha^{-1}$ ($kg.m^{-3}$).

Soil salinisation varies strongly between years, even at the same rates of water application and despite higher rates of precipitation. It is clearly more telling to analyze processes than interpret lumped water budgets.

Tables 5.10 and 5.11 show that the methodology followed allows to evaluate different irrigation scenarios (with free or forced drainage). Leaching requirements can be studied for different combinations of water quality and landuses (different crops, fallow). Calculated soil salinity levels over time are indicators of the sustainability of individual land-use systems.

Capillary rise and drainage.

The calculations of capillary rise presume steady state conditions in each time interval: the flux density from the saturated groundwater table to the root zone is (assumed) constant. Thus, the height of capillary rise at a certain suction head can be calculated for a chosen flux density, if the hydraulic conductivity is known (Koopmans, 1991).

The moisture tension profile is defined by the equation:

```
Z = KPSI / (KPSI + Flux) * DeltaPSI                                    (5.17)
```

where
Z is height of capillary rise (cm)
Flux is flux density ($cm.d^{-1}$)
KPSI is hydraulic conductivity ($cm.d^{-1}$)
DeltaPSI is suction head difference (cm)

Integration of this equation over the PSI-range from 0 (groundwater) to PSI of the root zone yields the maximum height of capillary rise above the groundwater table at a determined flux. The hydraulic conductivity is a function of the soil suction (PSI), which is known (calculated) for each time interval.

Capillary rise and 'deep percolation' are calculated in three steps:

1. Calculate the height of capillary rise for a flux density of 0.02 $cm.d^{-1}$ at initial soil suction (PSIini in cm).
2. Match this height (Zrise in cm) with the distance to the groundwater table (ZTRD in cm). If Zrise > ZTRD then there is capillary rise, and the flux has to be recalculated. Otherwise deep percolation occurs.
3. Calculate the fluxes (capillary rise or percolation).

The effect of the soil's pore geometry on the rates of capillary rise or deep percolation were evaluated by varying the value of ALFA. Fig. 5.14 is constructed for a fixed flux density of 0.02 $cm.d^{-1}$.

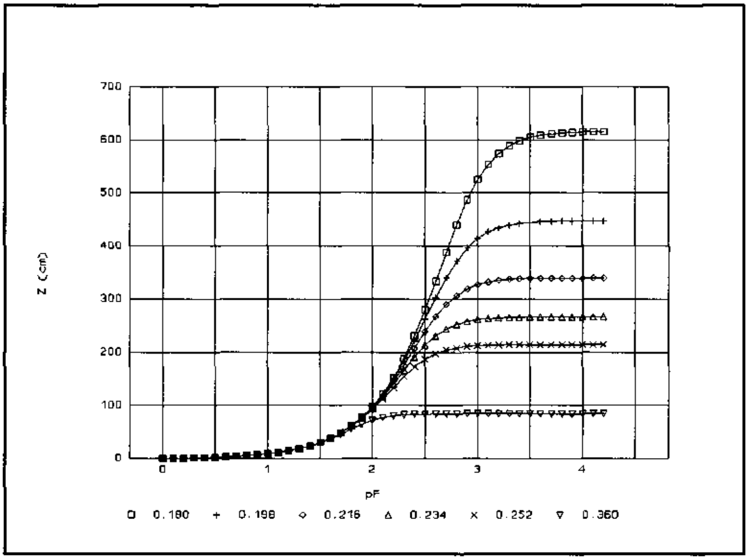


Fig. 5.14. Effect of the ALFA value.

A twofold increase of the value of ALFA resulted in a 7-fold decrease of the height of capillary rise in the high suction range.

The effect of the flux density on the height of capillary rise is shown in Fig. 5.15. ALFA was set to 0.19 cm^{-1} and the value of CR was set to values between 0.02 and 0.5 $cm.d^{-1}$.

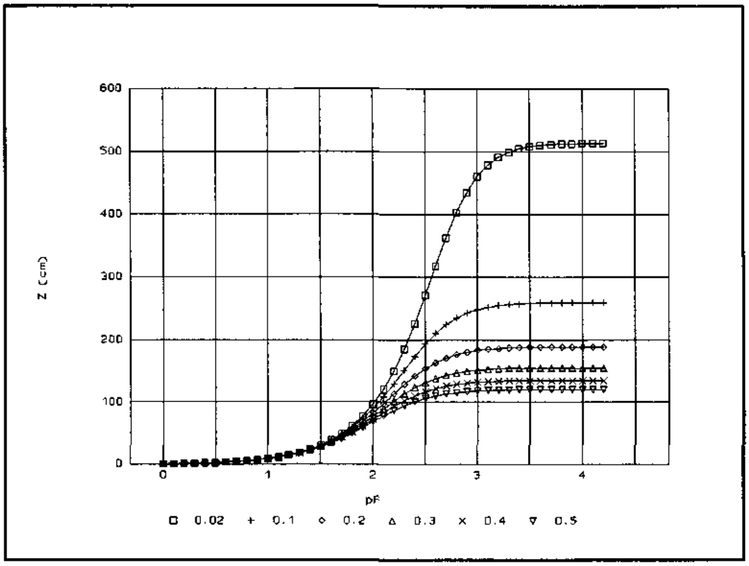
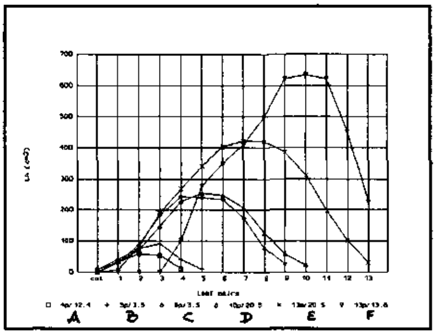


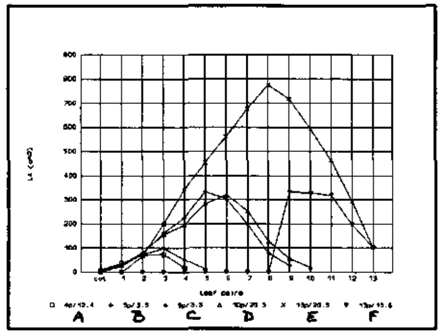
Fig. 5.15. Effect of the flux density (cm.d^{-1}).

5.3. Aspects of land use

Leaf area distribution

The leaf (area) distribution over the crop canopy is shown for the wet treatment (Fig. 5.16) and the dry treatment (Fig. 5.17). The x-axis gives the number of leaf pairs from the foot of the plant. In the figures, the leaf area of each leaf pair is specified for plants at different stages of development (and with different numbers of leaf pairs): from 4 leaf pairs and date 12.4 (A) till 13 leaf pairs at date 13.6 (F). Description of the leaf area distribution could be based on the number of leaf pairs, and on the shape and amplitude of the leaf area curve. It suggests a normal distribution until it skews (higher leaf numbers). At that time, the initial leaf pairs also have their leaf area reduced. Comparing Fig. 5.17 with Fig. 5.16, shows that the development rate is faster if water is in short supply.





Leaf area distribution of plants with different numbers of leaf pairs and different development stages .
Fig. 5.16. Wet treatment. **Fig. 5.17.** Dry treatment.

In general, leaves have a shorter life span than other plant organs. Leaves are formed, grow and die off continuously, so that individual leaves have different stages of development. But it is observed that the first leaf is the first to die. Leaves die when their relative leaf development reaches a threshold value (TLEAF). If drought stress occurs, leaves live shorter, because the rate of relative leaf development accelerates.

Fig. 5.18 shows the effect of TLEAF on LAI at PS1 level. The curve LAI1 presents LAI for a TSUM of 1470 °C d and a TLEAF of 900 °C. LAI2 presents LAI with no TLEAF (or TLEAF equal to TSUM). The dead leaf area is represented by the area between the two curves. From an RDS value that equals TLEAF over TSUM (in this case 0.61), dead leaf mass exists.

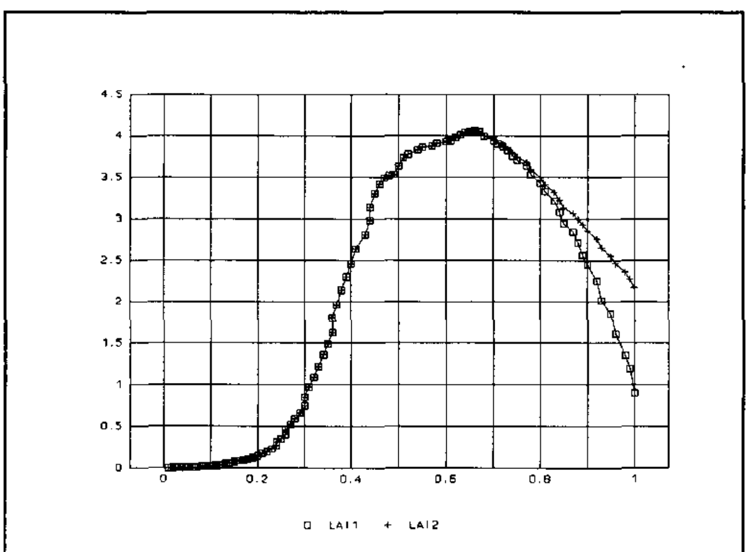


Fig. 5.18. Effect of TLEAF on LAI.

The rate of relative leaf development increases if drought stress occurs. Fig. 5.19 is constructed by assuming a fixed water shortage at RDS > 0.4 (CFWATER = 0.6). The effect of water shortage on the rate of leaf dying causes the difference between curves A and B. Curve A represents only the effect of water shortage. The further decrease of LAI in curve B is caused by accelerating the rate of leaf dying by EXP(1 - CFWATER), or in this case 1.49. The LAI value is almost zero at RDS = 0.85.

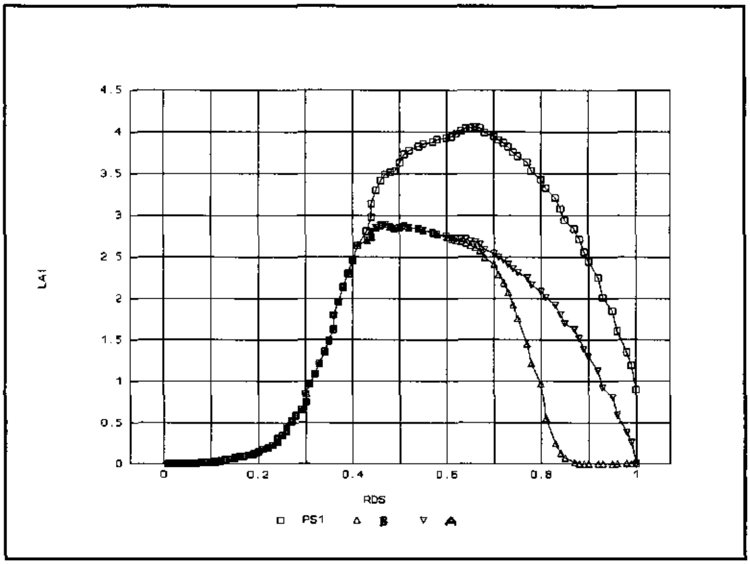


Fig. 5.19. Effect of water stress and rate of leaf drying on LAI.

Total Water Requirement (TWR)

By definition, there is no shortage of water in PS1. However it is tempting to calculate how much water one would have to provide to reach PS1 production. This could be done by adapting the water balance module to compute always the maximum rate of evapotranspiration (for unhindered crop production). Water requirements are then calculated for the level of production reached at PS1.

As a further simplification it is assumed that there is neither capillary rise nor drainage; and no change in soil moisture content over the crop season (constant PSI, KPSI and SMPSI values). Under such circumstances the maximum rate of water uptake by roots (MUR) varies only slightly between a minimum value at the beginning of the season when the rooting depth is minimum to a maximum value when the rooting depth is at its maximum.

The (assumed) constant values are found with the following equations:

```
PSI = 1000
KPSI = K0 * PSI ^ (-ALFA * LOG(PSI))
SMPSI = SM0 * PSI ^ (-GAM * LOG(PSI))
Rplant = 680 + .53 * PSIleaf
Rroot = 13 / (RDint * KPSI)
MUR = (PSIleaf - PSI) / (Rplant + Rroot)
```

The reference evaporative demand in the absence of a crop (Ebare) and in the presence of a crop (EM) are described by:

```
RHS = EXP(-2.1649 * 10 ^ -4 * PSI / (273 + T24h))

Ebare = E0 * (RHS - RHA) / (1 - RHA)
        Where Ebare = 0 if RHA = 1.

EM = Ebare * EXP(-LAI * Ke)
```

The theoretical maximum transpiration rate amounts to:

```
TRO = ETO - .05 * EO              'evaporative demand
CFLEAF = 1 - EXP(-LAI * Ke)       'standing leaf area
TC = 1 + (TCM - 1) * CFLEAF       'crop development
TRM = TRO * CFLEAF * TC
```

The total water requirement can now be adjusted:

```
TWR = TWR + EM + TRM
```

The TRM value cannot be negative nor can it exceed MUR. The calculated MUR value was 1.60 $cm.d^{-1}$.

Fig. 5.20 shows potential evapotranspiration over the crop season, split into its evaporation (EM) and transpiration (TRM) components for a land-use system with sunflower in Coria del Rio in 1993. The emergence date is 5 April.

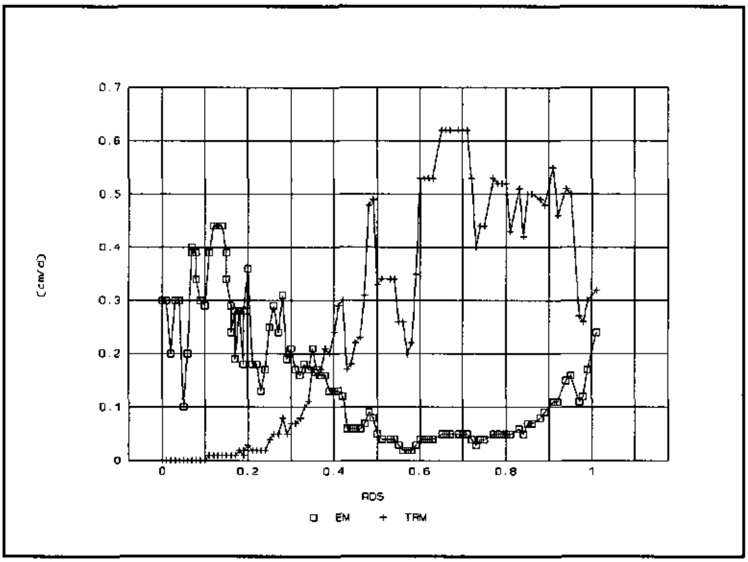


Fig. 5.20. Potential evapotranspiration for a constraint free scenario.

The TWR calculated for the full season was 392 mm, of which 237 mm is TRM and 156 mm is EM, or 60 and 40 % of TWR respectively. The reference evaporation (E0) was 409 mm for the same period. The dip of TRM at RDS = 0.58 (Fig. 5.20) is caused by a low ETO.

The water requirement for potential crop production is calculated as a function of environmental conditions (ETO and E0), soil characteristics (SMO, GAM, ALFA) and crop characteristics (LAI, Ke, TCM, PSIleaf, RD). Soil characteristics determine the rates of water flow through the soil and limits the rate of actual evapotranspiration.

Fig. 5.20 shows how transpiration increases as the leaf area builds up. At the beginning of the crop season, quite some water is lost through evaporation. A strategy to save water would have to include measures to limit water loss by evaporation, e.g. by applying a mulch layer.

Crop growth reducing factors.

Pests, diseases and weeds are biotic growth reducing factors. They cause yield losses that vary with the severity, timing and duration of the attack(s), the nature of the damage caused and the environmental conditions during the growing season (Rabbinge, 1986). This means that the economic returns of control measures vary between seasons, areas and management packages.

To explain the effects of growth reducing factors on crop growth and yield, three important aspects have to be considered (Rabbinge et al., 1994):

- population dynamics; e.g. the effects of crop and weather specifications on pests and their natural enemies;
- the nature of the damage done to the crop;
- the effects of management measures on the crop, the production environment, and on pests and their natural enemies.

The causes of production losses incurred in the course of the growth cycle can be grouped in four categories:

1. Availability of resources (e.g. less PAR or lower CFWATER)
2. Lower assimilation rate (EFF, AMAX and LAI)
3. Increased maintenance rate (greater r(org))
4. Decreased growth rate (smaller S(org))

Explanatory models of the effects of a particular pest on the growth and production of a crop are in many cases simulated for 'potential production' conditions (water and nutrients are not limiting). Assumptions are made to simplify parameterization of damage as a function of the population dynamics. For example, the harmful effects of a cereal leaf beetle attack on the growth and production of spring wheat (Rabbinge et al., 1994) are parameterized through the consumption rate of leaves (250 $cm^2.larva^{-1}.d^{-1}$). Effects of mites on the growth and production of potato are parameterized by postulating an increase in maintenance respiration leading to a decrease of the maximum rate of assimilation. The effects of yeasts on the growth and production of spring wheat are parameterized by assuming a decrease in light interception that is proportional with the logarithm of the yeast density, where the yeast population grows according to a logistic model.

Land evaluation methods cannot (yet) quantify yield and production of production situations where crop growth reducing factors are considered. Instead, damage can be evaluated by introducing default injury levels in the model as forcing variables without causal coupling of a pest (population dynamics) model with the model of the biophysical production potential (PS1). The procedure can thus estimate a yield loss level for a specified injury level at any stage of crop development.

Most of the common pests and diseases in sunflower cause loss of green leaf area. In Spain (Ordoñez, 1990), most damage to sunflower is done at the beginning of the crop cycle (germination, emergence and first leaf pair stages). Later attacks are not frequent and cause only limited damage. Preventive crop protection measures are the most effective, e.g. use of certified seed, use of resistant varieties, crop rotation, timing of sowing and avoiding conditions which predispose plants to infection, such as too high plant density, level of nitrogen fertilization and frequency of irrigations.

It is important to identify the different injury mechanisms and their levels of damage. To set a damage threshold value, the physical yield reduction has to be evaluated as well as the economic returns on crop protection measures.

Simulation of damage to sunflower by crop growth reducing factors yielded the results listed in Table 5.12 which shows the effects of injury mechanisms at relative development stages 0.0, 0.35 and 0.70. It was assumed that the injury effects last till the end of the crop cycle. In one particular case, referred in the table as RDS 0.70 to 0.80, the injury effects were assumed to be felt only during this development stage as a result of crop protection measures. Scenarios were run with a 10 % increase or decrease of relevant parameter values to represent the effect of particular injury mechanisms. This would mimic the limitated/decreased availability of resources, such as light (PAR) and water (CFWATER), a lower rate of assimilation (EFF, AMAX and LAI), higher maintenance costs (r(leaf)), and a generally lower growth rate (S(leaf)). The relative yield is compared with the control yield of a PS1 scenario for sunflower grown in Coria del Rio from 5 April 1993 onwards.

Table 5.12. Effects of injury mechanisms on sunflower yield.

nr	type	mechanism	RDS	relative yield
1	availability of light	PAR = 0.9 * PAR	0.0	0.92
2	" " "	PAR = 0.9 * PAR	0.35	0.92
3	" " "	PAR = 0.9 * PAR	0.70	0.95
4	" " "	PAR = 0.9 * PAR	0.70 to 0.80	0.98
5	availability of water	CFWATER = 0.9	0.0	0.76
6	" " "	CFWATER = 0.9	0.35	0.77
7	" " "	CFWATER = 0.9	0.70	0.88
8	" " "	CFWATER = 0.9	0.70 to 0.80	0.95
9	rate of photosynthesis	EFF = 0.45	0.0	0.92
10	" " "	EFF = 0.45	0.35	0.92
11	" " "	EFF = 0.45	0.70	0.95
12	" " "	EFF = 0.45	0.70 to 0.80	0.95
13	" " "	AMAX = 0.9 * AMAX	0.0	0.90
14	" " "	AMAX = 0.9 * AMAX	0.35	0.92
15	" " "	AMAX = 0.9 * AMAX	0.70	0.95
16	" " "	AMAX = 0.9 * AMAX	0.70 to 0.80	0.98
17	rate of assimilation	LAI = 0.9 * LAI	0.0	0.89
18	" " "	LAI = 0.9 * LAI	0.35	0.94
19	" " "	LAI = 0.9 * LAI	0.70	0.96
20	" " "	LAI = 0.9 * LAI	0.70 to 0.80	0.99
21	rate of maint. resp.	r(leaf) = 1.1 * r(leaf)	0.0	0.95
22	" " "	r(leaf) = 1.1 * r(leaf)	0.35	0.95
23	" " "	r(leaf) = 1.1 * r(leaf)	0.70	0.98
24	" " "	r(leaf) = 1.1 * r(leaf)	0.70 to 0.80	0.98
25	rate of growth	S(leaf) = 0.9 * S(leaf)	0.0	0.96
26	" " "	S(leaf) = 0.9 * S(leaf)	0.35	0.99
27	" " "	S(leaf) = 0.9 * S(leaf)	0.70	1.01
28	" " "	S(leaf) = 0.9 * S(leaf)	0.70 to 0.80	1.00

For cases 25 to 28, the 10 % decrease in S(leaf) means that the quantity of assimilates allocated to leaf growth in each time interval was diminished by 10 %.
In most cases the relative damage is less than 10 %, except for the scenarios with water stress. Injuries occurring after RDS = 0.70 inflict a relative damage of less than 5 %. The cases with water stress cause the strongest yield depressions because two main physiological processes are affected: depressed assimilation and accelerated leaf senescence (which also affects assimilation).

As expected, early injuries cause the greatest damage. It is striking that correcting a late injury (compare injuries that happen at RDS = 0.70 with injuries that last from RDS of 0.70 to 0.80) usually results in an increase of relative yield of less than 5 %.

Simulated injury mechanisms affect particular crop growth processes, and demonstrate the relative importance of these processes for yield formation. Four groups of injury mechanisms can be distinguished. In decreasing importance: i) Water stress effects, ii) AMAX, LAI, PAR and EFF effects, iii) r(leaf) effects, and iv) S(leaf) effects. Cases 27 and 28 even result in a greater yield than the control yield because less leaf mass requires less maintenance.

Some major pests/yield losses were not investigated, for instance seed consumption from the sunflowers' head by birds.

The procedure sheds some light on (the effects of) injury mechanisms and assesses the relative damage inflicted. At field level, the most severe damage is adequately estimated by judging the decrease in leaf area.

5.4. Conclusions and recommendations

Analyses of land-use systems generate values for the biophysical production potential (PS1) and the water-limited production potential (PS2). The main subjects dealt with in this study are:

- parameterization of weather, soil and crop,
- (new developments in) modelling of land-use systems with sunflower,
- model calibration and sensitivity analysis,
- selection of land-use systems for sustainable production.

Conclusions reached in this study and recommendations formulated are summarized in concise statements hereafter:

Parameterization of weather, soil and crop

Weather parameters

Temperature dictates crop development and therewith the duration of the growth cycle, the lifespan of leaves, and the rates of assimilation and maintenance respiration. Daily temperatures are generated with several (integration) methods in the calculations. Scenarios run to evaluate a variation of the average temperature by 2 degrees showed 1 to 6 %

difference in yield and differences in the length of the crop cycle of 10 days.

The temperature of the crop may differ from air temperature. When there is no shortage of water and transpiration is at the maximum rate, the canopy temperature is normally less than the air temperature because the energy uptake for vaporization of water lost in transpiration causes the canopy temperature to drop. If there is shortage of water, the canopy temperature may become higher than the air temperature, which explains why crop development accelerates under water stress.

For correct assessment of root activity, soil temperature data would be needed but these are not always available; the air temperature is used instead. Germination of seeds (and the duration of the germination phase) is particularly dependent on soil temperature and on soil water content. However, evaluating hourly air and soil temperatures over a long period has shown that average air and soil temperatures do not differ much during the growing season. Estimating the duration of the germination phase on the basis of air temperatures is not likely to produce a disturbing error.

Incoming solar radiation determines the levels of assimilation and evapo(transpi)ration. Calculation of the photosynthetically active radiation (PAR) is based on measured sun hours (SunH); these measurements are thought to be accurate to within 10%. Evaluations of measured and calculated radiations in Coria del Rio produced a 3 % difference. The conversion factor from incoming radiation to PAR was set to 0.5 (some other authors set this factor to 0.45). Results of scenarios evaluated for 10 % variation in the calculated PAR value show that yields increase with increasing radiation levels; the rate of change is slightly less than the rate of variation of PAR.

The effect of different evapo(transpi)ration values on the outcome of PS2 scenarios is modest: a difference of 10 % in E0 and ET0-values cause yield differences of less than 2 % in both years. Only with greater differences will yield variations become disturbing.

Rainfall sum and rainfall distribution are very important parameters in a region where the evaporative demand of the atmosphere is mostly in excess of precipitation. The ratio of evaporative demand over precipitation, called the 'aridity index' varies between 0.81 and 0.15 in the long term.

Soil parameters

Soil parameters influence crop performance, especially where water availability to the root system is periodically marginal, but relevant soil parameters are difficult to quantify. Measured water retention curves are desorption curves that cannot be introduced in the calculations straightaway because in a field situation desorption and resorption alternate. Resorption curves may differ considerably from desorption patterns. The use of a theoretical function based on total pore fraction and a texture-specific pore geometry factor (optimized to fit measured values) avoids systematic over-estimation of water availability but can only be of a generic nature.

Another matter of concern is the dry bulk density value that is used to convert gravimetric water content to volumetric water content and to calculate total soil porosity: it is considered constant. However, bulk density values vary as a consequence of soil tillage and soil compaction. The accuracy suggested by tabulated total pore fractions and texture-specific pore geometry factors in the table of generic values for the soil moisture curve is therefore misleading; calculation results demonstrate that these soil parameters could well be aggregated to less but broader texture classes.

Water stored in the rooted soil compartment must flow to the roots before water lost in transpiration can be replenished. The resistance to flow is expressed by its reciprocal value, the (un)saturated hydraulic conductivity of the soil at the momentary soil moisture potential. The KPSI-PSI relation is particularly difficult to establish. Measurements are best done in situ but there are no reliable methods known that can handle soil suctions beyond 1000 hPa. In the land-use systems studied, drought is the problem (not waterlogging) and soil moisture potentials may exceed 15000 hPa. The only method that claims to deal with such high suctions is the 'hot air method' but its operational value is generally considered to be low, inter alia because KPSI values are measured on a dislocated soil core of small volume that is hardly representative of an entire soil pedon, let alone of a field. Published KPSI-PSI relations extrapolate measured low-suction KPSI-values to the entire relevant KPSI range of 0 -> 15000 hPa, e.g. by extending a low suction KPSI-PSI relation (PSI < = 300 hPa) with a theoretical high suction function. The artificial nature of such broken curves and the (too) low flow rates suggested by them at PSI-values over a few thousand hPa makes it attractive to use an alternate notation that starts from the saturated hydraulic conductivity (K0) with a sigmoid KPSI-PSI pattern on the basis of a texture-specific pore geometry factor.

The main goal of the water budget calculations is to quantify the soil moisture content over the crop season as an indicator of the sufficiency of water for crop production. The effect of different hydraulic conductivity parameters can be evaluated by matching the generated soil moisture content with field measurements. Most of the variations found seemed caused by ALFA, a factor that expresses the effect of pore geometry on the KPSI-PSI relation. A higher ALFA value causes a lower KPSI and calculated water stress occurs later in the season.

Crop parameters

The specific leaf area (SLA) represents the total leaf area per unit dry leaf mass; the SLA value varies with the relative development stage of the crop and with growing conditions. It is generally true that sunflower forms thicker leaves as it develops so that the value of SLA decreases from a maximum value, early in the season, (SLAmax), to a minimum value at the end, (SLAmin). Thickening of the leaves, i.e. a decrease of SLA, is co-determined by the availability of water.

Varying the values of SLAmax and SLAmin by +/- 10 % resulted in up to 25 % variation in yield.

Values for relative maintenance requirements (r(org)) were borrowed from literature. There are indications that maintenance requirements vary (somewhat) with the availability of water. Introduction of low relative maintenance requirements (r(org)) resulted in yield differences up to 25 %, but the calculated final LAI values became too high to be true.

The PSI value at which no more water can be extracted from the soil and the plant wilts irreversibly does not just depend on the soil (as is wrongly suggested by definitions that put the 'permanent wilting point' at pF 4.2, which is a soil parameter) but on the value of the critical leaf water head (PSIleaf). PSIleaf values were approximated by plotting the volumetric water contents at permanent wilting on the corresponding soil moisture retention curve (range from 14500 to 22000 hPa). Inaccuracies in determinations of the bulk density, Θ-value and pF curve outweighed any difference between varieties.

New developments in modelling of land-use systems with sunflower

Integration of phenological parameters in crop models permits to better relate crop growth and development. This requires the description of sunflower growth stages, identifiable in the field and typical of specific varieties. The model describes the state of the land-use system for discrete time intervals between emergence and maturity: the period of active crop growth. The periods between sowing and germination and the ripening off phase are not considered in the calculations.

The mass fractions of assimilates produced that are allocated to each plant organ are fractions of the gross assimilate production in a particular time interval. Tabulated allocation fractions have no relation with phenology. Assimilate fractionings were computed from organ weights as recorded in partial harvests.

Increments in organ mass recorded in successive partial harvests represent the net assimilate production between harvests multiplied by the efficiency of conversion from assimilate to structural organ dry matter. To compute the quantities of assimilates allocated to each plant organ between partial harvests, one must quantify gross assimilation and the compounded losses to maintenance and growth respiration between harvests. Obviously, the reconstructed fractioning values resulted in calculated plant organ masses that are the same as found by partial harvesting. Ratios of dry organ mass over leaf mass suggest a more consistent crop development pattern than obtained with the use of tabulated fractionings. This suggests that plants are influenced by environmental factors in the actual partitioning of their assimilates.

Light response curves relate incoming radiation with gross assimilation at a defined temperature, for crops with a defined photosynthetic pathway. These curves are fully described by two parameters: the light use efficiency at low light intensity (Eff) and the maximum (gross) rate of assimilation at light saturation (AMAX). The calculation of AMAX is based on set AMAX-to-temperature relations. Another approach is to infer AMAX from measured crop growth, using organ masses recorded in partial harvests to compute the gross potential assimilates production.

Temperature influences AMAX only above a threshold value; diurnal temperature fluctuations affect assimilation (during daytime only) and maintenance respiration. Therefore a daily course of temperature is calculated from maximum and minimum air temperatures by assuming a sinusoidal temperature curve during daytime and an exponential curve at night. The equivalent temperatures calculated may differ from the mean of the maximum and minimum daily temperature by as much as 2 °C.

The level of radiation used in the calculations is based on radiation that reaches the top of the atmosphere. Only a fraction of this reaches canopy level, determined inter alia by atmospheric transmissivity. The approximated radiation correlated well with measured radiation values. Any deviations are probably rooted in the estimation of atmospheric transmissivity (using the semi-empirical Ångström relation) and net longwave radiation (which depends strongly on daily temperature).

Evapotranspiration values calculated according to Penman-Monteith require basic information on the net radiation value, the air heat capacity, albedo(s) and resistances. The value of the air heat capacity can be set as a constant. Albedos for water, grass, sunflower and bare soil were measured. Aerodynamic resistances and crop resistances are postulated. Other methods may require (much) less input data but they make use of an ill-understood "crop coefficient" to calculate the water needs of a particular crop. The general Penman-Monteith equation can be used to calculate water loss from a water surface, a bare soil, a reference crop or an actual crop (E0, Esoil, ET0, ETcrop). The last two calculations can be used to approximate the value of crop coefficient: Kc = ETcrop / ET0. As some of these calculations are rather speculative, it was assumed that the maximum Kc-value tabulated for a specific crop defines the maximum value of ETcrop. Alternatively, calculations of daily evapotranspiration losses can be done outside the crop growth module, by first running a PS1 scenario and output the generated values of LAI from which the crop height, and aerodynamic and crop resistances are calculated.

Model calibration and sensitivity analysis

Sensitivity analyses at the level of Production Situation 1 examine the effects of photosynthetically active radiation (PAR), temperature (Tavg), specific leaf area (SLA), assimilates allocation (fr(org)) and maintenance respiration rates (r(org)) on the length of plant growth (LPG), yield (YIELD), harvest index (HI) and leaf area duration (LAD). The results of the sensitivity analyses are subsequently used to judge the adequacy of the crop parameter values used, by correlating selected parameters with measured field data:

1. TSUM with length of growing period.
2. r(org) with observed total dry matter production.
3. TLEAF with observed LAI.
4. fr(org) with observed dry matter ratios.

These tests produced the trends previously established on the basis of phenology description/characterization, and dry matter fractioning. The LAD was used as a bench mark to judge the adequacy of the procedure.

Sensitivity analyses at the level of Production Situation 2 examine the compound effects of evapo(transpi)ration rates (E0 and ET0), hydraulic conductivity function (K0 and ALFA), soil moisture retention curve (SM0 and GAM) and selected crop and soil parameters (PSIleaf, TRM and RDm) on yield (YIELD), leaf area duration (LAD), first occurrence of water stress (CFWone) and cumulative transpiration (sumTR). The results of the sensitivity analyses are used to judge the adequacy of the crop and soil parameter values used, by correlating selected (calculated) parameter values with measured field data:

1. KPSI function with measured soil moisture content.
2. CFWone value with the first irrigation date.
3. Yield with observed maximum LAI and LAD.

These tests confirm the trends previously established by means of water budget calculations. The CFWone value was taken as an indicator of the correctness of the land-use system descriptions.

Differences between varieties were evaluated at the level of Production Situation 1 by considering differences in Specific Leaf Area, in fractioning and in maintenance respiration needs. Two other crop characteristics are strongly variety-specific: the heat requirement for full plant development (TSUM), and the heat requirement for full leaf development (TLEAF). Differences in yield appeared to be strongly correlated with differences in LAD.

At the level of Production Situation 2, differences between varieties were evaluated for three crop characteristics: the critical leaf water head (PSIleaf), the maximum turbulence coefficient (TCM) and the maximum rooting depth (RDm). The relative performances of varieties grown under different water regimes suggest different PSIleaf values, as discussed in section 4.3, and the same holds for the TCM value, which was based on published crop coefficients. The RDm value is not a true constant but is co-determined by complex plant and soil interactions; sunflower develops a deeper rooting system in soils of low bulk density.

Variation of the PSIleaf value had only a minor effect. As expected, a greater PSIleaf-value is associated with a greater sumTR value, showing that the crop was able to extract more water from the soil. Variation of the TCM value has the same effect as variation of E0 and ET0 values. Variation of RDm affects directly the quantity of available water and causes the value of CFWone to move back or forth. By and large, yields increase with an increase in rooting depth if water availability is a limitation. The maximum rooting depth of a crop (variety) may be dictated by soil specifications: measured values are strongly preferred over generic estimates.

Biophysical production potential (PS1)

The biophysical production potential could be realized in the experiments done at Coria del Rio and shows that sunflower yields in the region can technically be doubled. Conventional field experimentation does not explain temporal and spatial variabilities of production. These can be evaluated through dynamic modelling provided that the available basic data are adequate. The limited number of environmental and management variables required make the use of the program practical.

Water-limited production potential (PS2)

Historic weather data can be used to evaluate the long-term success of a land-use system. The biophysical yield and production potentials (PS1) over the years reflect the effects of changing environmental conditions on crop production. Yield potentials varied between 3948 and 4844 $kg.ha^{-1}$. The variation of the yield component of the water-limited (rainfed) production potential (PS2) adds the effect of variable availability of water. Water scarcity reduced yields of rain-fed plots to less than 800 $kg.ha^{-1}$. Water is the main limiting crop production factor in Andalusia.

Production and yield are dependent variables; land suitability classification must take variable system specifications into account. Average values of production and yield can at best be used as indicators and for comparison.

The use of generalized water sufficiency indexes (or aridity indexes) can be misleading. The CFWone value is calculated on the basis of a score of dynamic and interacting system parameters and is a good indicator for planning irrigation scheduling. Irrigation scenarios will normally be designed to push the CFWone value as far as possible towards the end of the cropping season through an optimal combination of application doses and timing.

Selection of land-use systems for sustainable production

Long term weather specifications

An evaluation of long-term weather data gives a first indication of crop production possibilities and constraints (level of radiation, temperature, precipitation and sun hours) and of specific cropping activities (sowing date, harvest period).

Data screening for missing or corrupt weather data reveals data consistency, data correlation and data ranges, particularly when comparing such attributes as day length and daily sunshine hours, global and extraterrestrial radiation, global radiation and daily sunshine hours, daily temperature fluctuation and atmospheric transmissivity, and humidity and precipitation.

The correlation between measured and simulated values helps to estimate and patch missing values and to judge data accuracy. Data recorded as integers are not adequate in all cases. An example would be sun hours where the minimum error is half an hour in a maximum number of, say, 14 hours; rounding off to full hours can result in SunH > DL.

Average daily temperature values will still show the seasonal course of temperature. One intermediate measurement between 7 o'clock and 13 o'clock would suffice to characterize daily relative air humidity. By and large, the fit with simulated values is quite good. Between week 20 (May 14) and week 40 (October 1) it is very probable that a single shower supplies most of the weekly precipitation. The period has also the lowest probability of rain events. The extent to which precipitation meets the evaporative demand of the atmosphere is shown by the 'aridity index', the ratio between total precipitation over total (potential) evaporation. Wind speed data also show a seasonal pattern that can be used in patching missing data.

Soil salinity

In the calculations of the water-limited production potential, the water balance routine keeps track of all water fluxes in or out of the rooted surface compartment (precipitation, irrigation, evaporation, transpiration, surface runoff and capillary rise or deep, percolation/drainage). Effects of salinity are made visible by defining the salt load of each water flux. Osmotic pressure increases the total soil moisture potential and affects negatively the ease of water uptake for transpiration and consequently the rates of assimilation and growth/production.

Alternative irrigation strategies, with different timing and doses of water input, (and different levels of water stress), can be evaluated. Similarly, leaching requirements can be tested by defining a 'permissible level' of soil salinity under alternative irrigation schedules, landuses (different crops and/or fallow) or depths of the groundwater. Calculated soil salinity levels over time are indicators of the sustainability of landuse.

The level of soil salinity is commonly related to the electric conductivity of a saturated soil paste at 25 °C. However, the real soil water content varies strongly between sites and between years and the actual soil salinity level (EC) may be several times greater than EC_e. It is conceptually better to relate yield depression by excess electrolytes in the soil solution not only to EC_e but also to (fluctuations) of the soil moisture regime.

Soil salinity may develop differently in different situations despite similar rates of water application and precipitation. It is clearly more telling to analyze processes than interpret lumped (soil) water parameters.

Capillary rise and drainage

Calculations of capillary rise rates presume steady state conditions in each time interval: integration of the flux density equation over the PSI-range from 0 (groundwater) to PSI of the root zone yields the maximum height of capillary rise above the groundwater table at a determined flux.

Fluxes are assumed to depend entirely on actual soil suction and depth to groundwater. The calculated fluxes react sharply to changes in the value of ALFA which is a soil characteristic. the fluxes vary also with the integration step. An integration step of 0.01 pF seems to give acceptable accuracy in a reasonable computation time.

Leaf area distribution

Leaf area changes over time. The model does not consider canopy architecture, even though differentiating the leaf area over the canopy would allow to evaluate processes that occur only in certain leaf layers, or to differentiate photosynthesis over the canopy. Instead, leaf area distribution is represented by one leaf area index for the full crop canopy.

Total Water Requirement

The water balance module can be used to calculate water (input) requirements for a maximum rate of evapotranspiration (i.e. for unhindered crop production). The water requirement for potential crop production varies with environmental conditions (ET0 and E0), soil characteristics (SM0, GAM, ALFA) and crop characteristics (LAI, Ke, TCM, PSIleaf, RD).

Crop growth reducing factors

Quantified land evaluation methods cannot (yet) estimate yield and production as dependent variables of crop growth reducing factors. The degree of damage can only be evaluated by introducing exogenous default injury levels in the model without causal coupling with the crop production model.

Data

The input data required for land-use systems analysis are grouped in four categories: weather data, soil data, crop data and management data. The data come from two sources: literature review and field/laboratory measurements. Field measurements are direct measurements or values compounded from several measurements. All weather data come from a weather station but some derived weather data are calculated.

Besides spatial data considerations, the temporal data resolution is important. The one day interval used in the model is a trade off between the availability of data and the dynamics of the system: it is too long to study the effects of short duration precipitation and/or high irrigation intensities.

Final remarks

Simulation models of crop growth and associated uptake of water involve hundreds of state and rate variables and input data. The availability of data for dynamic simulation is usually marginal even if time intervals of one day are used. Land-use systems analysis with daily data is done at a high level of aggregation: the lower data requirements go at the cost of lower accuracy. In this study procedures were used to check the accuracy and reliability of the generated output. But new procedures will have to be developed to curb the use of generic data values and empirical relations. Field experimentation must preferably be done in established experimental farms, to minimize errors of data collection, and to permit use of the data in studies at several levels of abstraction/aggregation.

Efforts have to be made to further elaborate the role of evapotranspiration in the crop model. The evaporative demand of the atmosphere has a great impact on the outcome of the water balance calculations. Empirical parameters such as the crop coefficient (Kc in the maximum turbulence coefficient, TCM) can then perhaps be avoided.

The description of the unsaturated hydraulic conductivity of soils deserves further attention; functions must be developed that reliably describe KPSI for the full range of possible soil water potentials, especially for land-use systems where water availability is marginal.

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ANNEXES (available on request)

A. SOIL DESCRIPTION, ANALYTICAL DATA AND FIELD MEASUREMENTS.

A.1. Soil profile description
File SPD.TXT

A.2. Analytical data
Soil analysis, data from 1993 and 1994, *file SOILANA.TXT*
Bulk density, *file S_BD.TXT*
pF measurements, *file S_PF.TXT*
Hot-air method, *file S_HAM.TXT*
Multi-step outflow method, *file S_MSOM.TXT*

A.3. Field measurements
Soil moisture, data from 1993, *file SMOIST93.TXT*
Soil moisture, data from 1994, *file SMOIST94.TXT*
Soil tensiometry, data from 1993, *file S_TENS93.TXT*
Soil tensiometry, data from 1994, *file S_TENS94.TXT*
Infiltration measurements, file *S_IM.TXT*

B. SUNFLOWER DESCRIPTION, PLANT ANALYSIS AND CROP MEASUREMENTS.

B.1. Morphological description of sunflower cultivars
File VARMORF.TXT

B.2. Analytical data
Plant analysis, data from 1993 and 1994, *file PLANTANA.TXT*
Oil quality, data from 1993 and 1994, *file SEEDANA.TXT*

B.3. Crop measurements
Data from 1993, *file CROP93.TXT*
Data from 1994, *file CROP94.TXT*

C. WEATHER DATA

C.1. Weather data of Coria del Rio, 1993.
File: CORIA93.DAT (DOY, Tmax, Tmin, PREC, RHA, SunH, Wind)

C.2. Weather data of Coria del Rio, 1994.
File: CORIA94.DAT (DOY, Tmax, Tmin, PREC, RHA, SunH, Wind)

C.3. Weather data of Coria del Rio, 1971 to 1995.
Files: CDR71.DAT through CDR95.DAT (DOY, Tmax, Tmin, PREC, RHA, SunH, Wind)

C.4. Weather data files for small programs:
File M.DAT (with climatic data as Tmax, Tmin, SunH) for programs *AMAX.BAS* and *FRAC.BAS*.
File MM.DAT (climatic data: latitude, Tmax, Tmin) for programs *D-FRAC.BAS* and *DAYTEMP.BAS*.
File TDIFF.DAT (data: LAT, Tmax, Tmin, RHA, ETO, EO, LAI) for program *TEMPDIFF.BAS*.

D. LISTING OF PROGRAM MODULES AND DATA FILES

D.1. Main program: *file SUNFLOR.BAS*

Overview of computer program SUNFLOR.BAS:

Land use systems with sunflower were analysed with the computer program SUNFLOR.BAS. This overview shows the structure of the main program and its subroutines.

a. Main program:

```
'PART I: INITIALIZATION

GOSUB HeaderAndAim                                    'Show the program set-up
AnewAgain:                                                  'Rerun the program
GOSUB PSSelection           'Select the Production Situation to be analysed
GOSUB DataInput           'Input weather, crop and soil data from data files
GOSUB Management                                        'Input management data
GOSUB Initialize                                           'Set initial values


'PART II: INTERVAL CALCULATIONS

NEXTCYCLE:                                         'Loop for daily calculations
GOSUB ClimaCalc             'Calculate DL, temperatures, radiation  and ET
GOSUB RDSCalc                        'Calculate relative development stage
GOSUB AssimCalc                   'Calculate gross assimilate availability
GOSUB FractCalc                      'Calculate fractioning of assimilates
GOSUB MaintCalc                                'Calculate maintenance costs
GOSUB GrowthCalc                             'Calculate dry matter increment
IF RDS < 1 THEN GOSUB NewCycle       'Calculate NEW RDS and goto NEXTCYCLE


'PART III: OUTPUT & COMPLEMENT

GOSUB OutPutOnScreen                          'Show the results on the screen
GOSUB OutPutOnFile                                'Write the results to a file
'WaterBalance     'Calculate the water balance, called from AssimCalc for PS2
IF VAL(PSSELECT$) = 3 THEN GOTO FERTILIZERS  'Calculate the fert.requirements
'LIMITS                               'Account for the limits of calculations
GOSUB NewRun                  'Quit or resume the program and clear arrays
EXITING:                                                    'Exit the program
END                                                     'END of MAIN Program
```

b. Subroutines

```
HeaderAndAim:                              'Subroutine to show the program set-up

PSSelection:    'Subroutine to select the Production Situation to be analyzed

DataInput:                  'Subroutine to input climatic, crop and soil data

'1) Input a CLIMATIC FILE and read the data
INPUT: SiteLabel$, LAT, LON, ELEVATION
INPUT: Day, TMAX, TMIN, PREC, RHA, E0, SUNH, ET0

'2) Input a CROP FILE, list the crops and read the data
INPUT CROPLABEL$
INPUT C3C4$, T0, TSUM, TLEAF, TLOW, RDSroot, RDm, RDint, PSIleaf
INPUT SLAMAX, SLAMIN, ke, TCM, RLEAF, RRT, RSTEM, RSO
INPUT ECLEAF, ECROOT, ECSTEM, ECSO, NSO, NSTRAW, PSO, PSTRAW
INPUT NRPTS
FOR Y = 1 TO NRPTS INPUT CRDS(Y), FRLEAF(Y), FRROOT(Y), FRSTEM(Y), FRSO(Y)

'3) Input a SOIL FILE, list the soils and read the data
INPUT SOILLABEL$
INPUT SM0, GAM
INPUT PSImax, K0, ALFA, AK
INPUT S0, Ktr


Management:             'Subroutine to input management data from the screen
INPUT: GERDAY; SEED; MORT
```

```
IF PSSELECT$ <> "1"                                  'Supplemental data for PS2
   INPUT: PSIINT; ASSC; SSINT; ZTINT; FIXZT$

IRRIGATIONinput:                                       'Irrigation data for PS2
INPUT: nr of IRRIGATIONS; Date; Gift


Initialize                 'Subroutine to set initial values and clear arrays
' Reset counters and initial values; clear the arrays with calculated results
' General, soil and crop constants and functions


ClimaCalc:            'Subroutine to calculate DL, temperatures and radiation
'Order: DLcalc; TempCalc; RadCalc
'Check for too low temperatures and high amplitudes


RDSCalc:                   'Subroutine to calculate relative development stage
'Calculate new RDS
'Check for zero development


AssimCalc:            'Subroutine to calculate gross assimilate availability
Order: AMAX; PAR; SLA; LAI; Fgc; CFWATER; FGASS


FractCalc:            'Subroutine to calculate the fractioning of assimilates
' Calculation of FR(org) by interpolation between inflection points


MaintCalc:                         'Subroutine to calculate maintenance costs
'Order: REFMAINT; cf(temp); ACTMAINT


GrowthCalc:                         'Subroutine to calculate dry matter increments
'Order: GAA(org); NAA(org); DWI(org); S(org); DEADLEAVES; TDM ;TLDM


OutPutOnScreen:       'Subroutine to print calculation results on the screen
PRINT: Day   LAI   LIVsleaf   SLeaf   SRoot   SStem   SSO   TDM   CFWATER

WaterBalance:                       'Subroutine to calculate the water balance
'Calculate CFWATER
'Check for wet conditions, dry conditions and shallow ground water table


FERTILIZERS:               'Subroutine to calculate the fertilizer requirement
'Calculate the fertilizers required for a pre-defined attainable production


NewCycle:                      'Subroutine to account for a new time interval
'Define the new time interval
'Check for too long growing period


LIMITS:    'Listings of non-viable scenarios defined in different subroutines
CropOutCold:                            'reject systems with LOW TEMPERATURES
CropOutAmpl:                       'reject systems with (TMAX - TMIN)4 > 18 °C
TooLongOnField:                   'reject systems with TOO LONG growing period
CROPOUTDRY:                               'reject systems with LETHAL DROUGHT
CROPOUTWET:                               'reject systems with LETHAL WETNESS
SHALLOWWATER:                            'signal (sudden) SHALLOW GROUNDWATER


NewRun:          'Subroutine to quit or resume the program and clear arrays
```

D.2. Other programs:

LENGTH.BAS to compute the length of growing season.
FRAC.BAS to compute partitioning fractions.
D-FRAC.BAS to compute partitioning fractions.
AMAX.BAS to compute the assimilation rate.
DAYTEMP.BAS to compute the daily course of temperature.
TEMPDIFF.BAS to compute the canopy temperature.
PENMAN.BAS to compute the evapotranspiration rate.
TEMPERAT.BAS to compute seasonal daily temperature.
CR&D.BAS for flux density calculations.

D.3. Files

Harvest file: X.DAT for program *FRAC.BAS*.
Crop file: SUNFL.DAT for program *D-FRAC.BAS*.
Crop file: SUNFLOR.DAT for program *SUNFLOR.BAS*.
Soil file: CDRSOIL.DAT for program *SUNFLOR.BAS*.

SUMMARY

Quantified analysis of land-use systems is concerned with the functioning of a defined land utilisation type (with defined crop and management specifications) on a defined land unit (with defined weather and soil/terrain properties) over a defined period of time.

Land evaluation itself compares the requirements of land use with the qualities of the land, for scenarios with defined use of inputs.

Production potentials are calculated for various hierarchical production situations: the biophysical production potential (PS1), the water-limited production potential (PS2) and the nutrients requirement for target production (PS3). The higher the level of aggregation, the fewer input data are required but at the expense of a lower relevance to common land users.

Chapter one of this thesis explains the aim of this study: to develop a methodology for quantified analysis of specific land-use systems with sunflower.

Chapter two characterizes the land-use systems studied, and describes the physical production environment. Characteristic features of Andalusia occidental (climate, geomorphology and soils) are given. The land unit under study is described by its climate (weather) data, and its soil and terrain data. The climatic data include daily values of air temperature, relative air humidity, sun hours, precipitation and wind speed. The land unit has Cambisols with a loamy texture and is situated in the alluvial plain of the Guadalquivir river. A land utilization type is characterized by i) crop and variety data, and ii) management data. Three varieties of sunflower were grown: Florasol, Islero and Isostar. Management data include sowing date and density, initial soil moisture conditions, and drainage/irrigation specifications.

Chapter three describes the field experimentation and materials and methods are discussed. The cultivation activities made use of basic field techniques, e.g. a crop calendar, tillage practices, fertilization rates, irrigation and crop protection measures as usual in the region. The data collected include weather, crop and soil parameters necessary to describe dynamically potential production and water-limited potential production.

Dynamic modelling is described in chapter four. An outline of the model is given for the defined production situations. New developments in sunflower modelling concern the descriptions of phenology, dry matter partitioning, assimilation, temperature, radiation and evapotranspiration. Finally model calibration and sensitivity testing is discussed.

Chapter five discusses production potentials of land-use systems with sunflower and specific aspects of land (weather specifications, soil salinity and capillary rise) and of land use (leaf area distribution, total water requirement and crop growth reducing factors). Conclusions and recommendations are presented.

SAMENVATTING

Kwantitatieve analyse van landgebruikssystemen beschouwt het functioneren van een bepaald landgebruikstype (met gedefiniëerd gewas en bedrijfsvoering) op een bepaalde landeenheid (met gedefiniëerde weer- en bodem/terrein-eigenschappen) gedurende een bepaalde tijdsspanne. Landevaluatie vergelijkt de eisen van het landgebruik met de hoedanigheden van de landeenheid, voor scenarios met gedefiniëerde (sets van) productiemaatregelen.

Productiepotentiëlen worden berekend voor een aantal 'productiesituaties': het biophysisch productiepotentiëel (PS1), het water-beperkte productiepotentiëel (PS2) en de hoeveelheid nutrienten, die moet worden toegevoegd voor realisatie van een gedefiniëerd productieniveau (PS3). Deze productiesituaties zijn hierarchisch geordend van PS1 tot PS3; hoe hoger het niveau van abstractie, des te geringer is de behoefte aan input data (en des te geringer is de relevantie van de scenarios voor de 'normale' landgebruiker).

Hoofdstuk 1 van deze studie gaat in op het doel van het onderzoek: het ontwerpen van een methodologie voor kwantitatieve analyse van gedefiniëerde landgebruikssystemen met zonnebloem in Andalusië, Spanje.

Hoofdstuk 2 beschrijft de bestudeerde landgebruikssystemen en de productie-omgeving. Karakteristieke eigenschappen van west Andalusië (klimaat, geomorfologie en bodems) worden behandeld. De bestudeerde landeenheid wordt beschreven door haar klimaat/weergegevens en bodem/terrein-specificaties. De gebruikte primaire weergegevens zijn beperkt tot dagelijkse waarden van de maximum- en minimumtemperatuur, de relatieve luchtvochtigheid, het aantal dagelijkse zonne-uren, de neerslag en de windsnelheid. De landeenheid wordt gekenmerkt door Cambisols met een lemige textuur en is gesitueerd in de alluviale vlakte van de Guadalquivir rivier. Het landgebruikstype wordt gekarakteriseerd door gewas/varieteits-gegevens en managementspecificaties. Drie zonnebloemvarieteiten werden bestudeerd: Florasol, Islero en Isostar. De bedrijfsvoering wordt gekarakteriseerd door fysieke kenmerken: zaaidatum en zaaidichtheid, initieel bodemvochtgehalte en drainage/irrigatie-kenmerken.

Hoofdstuk 3 beschrijft het veldonderzoek, de experimenten en de toegepaste methoden en materialen, en besteedt aandacht aan de gewaskalender, met grondbewerking, bemestingsmaatregelen, irrigatie en gewasbescherming als in de regio gebruikelijk. De verzamelde gegevens omvatten alle weer-, gewas- en bodemparameters welke nodig zijn voor een dynamische karaterisering van het biofysisch en waterbeperkte productiepotentiëel.

Hoofdstuk 4 schetst het gebruikte dynamische gewasgroeimodel. Nieuwe ontwikkelingen in de modellering van de groei en productie van zonnebloem hebben betrekking op de beschrijving van de fenologie, de droge-stofverdeling, de assimilatie, en de invloed van temperatuur, straling en evapotranspiratie. Het hoofdstuk wordt afgesloten met een modelcalibratie en een onderzoek van de gevoeligheid van het model voor variaties in de waarden van cruciale systeemparameters.

Hoofdstuk 5 behandelt de productiemogelijkheden van landgebruikssystemen met zonnebloem en van de invloed van specifieke bodem/land-eigenschappen (weergegevens, niveaux van bodemverzouting, de invloed van capillaire opstijging) en van aspecten van landgebruik (watergebruik, groeireducerende omstandigheden). Het hoofdstuk wordt afgesloten met de voornaamste conclusies en aanbevelingen.

CURRICULUM VITAE

Jorge Manuel Cardoso de Barros was born on 30 September 1954, in São Pedro do Sul, Portugal. His primary and high school education was based on contributions by seven schools in Mozambique and Portugal. At the end of 1973 he started his studies in Agronomy at the University of Lourenço Marques (now Maputo), Mozambique. The political turmoil at the end of portuguese colonialism, and the independence of Mozambique were not conducive to academical progress but nonetheless very intensively lived: the 'pen' was replaced by the 'red book' of the Mozambican People's Liberation Forces. Some years and some burlesque episodes later, reality became stronger than romanticism; in 1985 he is back in school, in a mood of self "reconversion". He graduated as an agronomic engineer in 1990, with a specialisation in rural engineering. From 1990 to 1992 he followed the M.Sc. Course on Soil and Water, specialisation irrigation, at Wageningen Agricultural University. In August 1992 he started the present research on quantified land evaluation on a grant from the Netherlands University Fund for International Cooperation (NUFFIC). He worked in Wageningen (Department of Soil Science and Geology) and in Seville (Institute of Natural Resources and Agrobiology) where field research was done in 1993 and 1994.