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WOFOST: a simulation model of crop production

C.A. van Diepen[1], J. Wolf[2], H. van Keulen[3] & C. Rappoldt[4]

Abstract. The WOFOST simulation model is a tool for analysing the growth and production of field crops under a wide range of weather and soil conditions. Such an analysis is important first to assess to what extent crop production is limited by the factors of light, moisture and macro-nutrients, and second to estimate what improvements are possible. The theoretical concept of a production situation, as modelled by WOFOST, is explained, as is the hierarchy of potential production and water-limited and nutrient-limited production situations in the analysis. The organization of the computer files in the model, the structure of the FORTRAN source program and the available standard sets of data are described briefly.

The functions of the most important program sections are discussed. The model can be implemented on many kinds of computers. It can be used on its own, for site-specific studies of agricultural production potentials. But it can also be coupled to Geographic Information Systems for regional studies, or be used as a data generator for regional agro-economic models. The data on climate, soil and crop, needed for the calculations with WOFOST are specified. However, the general scarcity of comprehensive datasets forms a major constraint for the widespread use of the model in land evaluation.

INTRODUCTION

WOFOST is the acronym for WOrld FOod STudies. It is the name of a model for simulating the growth of crops and was developed by the Centre for World Food Studies in Wageningen, the Netherlands, in cooperation with the Agricultural University and the Centre for Agrobiological Research (CABO). The version of the model described here is called WOFOST4.1, which is the standard version for use on microcomputers (van Diepen *et al.*, 1988). The model describes the growth and production of annual crops in physical terms determined by crop species, soil type,

[1]Netherlands Soil Survey Institute (STIBOKA), PO Box 98, 6700 AB Wageningen.
[2]Centre for World Food Studies (CWFS), Wageningen.
[3]Centre for Agrobiological Research (CABO), PO Box 14, 6700 AA Wageningen.
[4]Department of Theoretical Production Ecology, Agricultural University, PO Box 14, 6700 AA Wageningen.

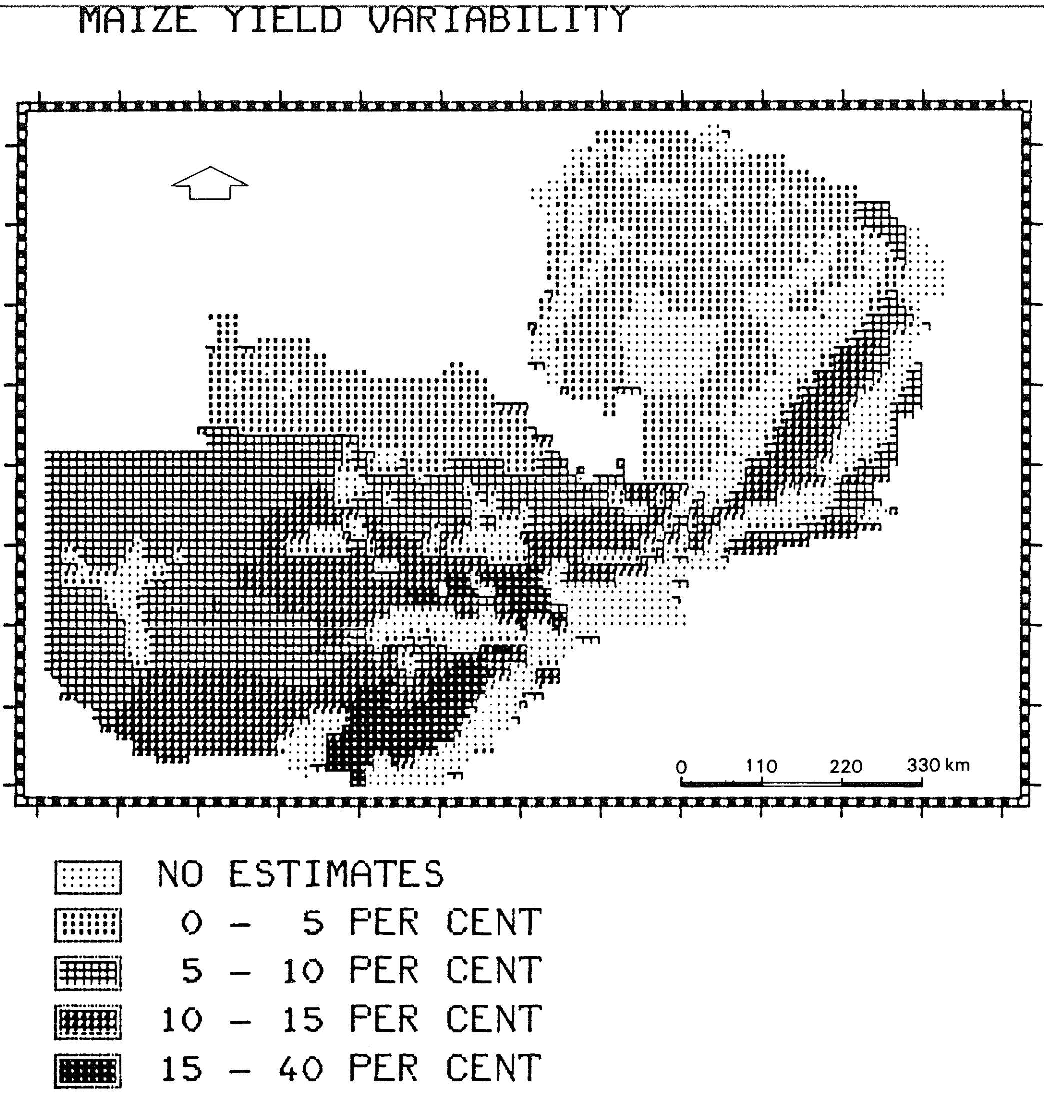

Fig. 1. Map of variability (coefficient of variation; per cent) in calculated water-limited grain yields of maize in Zambia.

hydrologic conditions and weather during the growing season. In principle, the model is applicable anywhere where crops are produced although the model has been developed primarily for agriculture in the tropics.

OBJECTIVE

The WOFOST model is designed for calculating the agricultural production potential for selected combinations of crop, soil and climate. The calculated theoretical yields allow one to evaluate the relative importance of the principal constraints to crop production, such as light, temperature, water, and the macro-nutrients nitrogen, phosphorus and potassium. This information is used to assess reasonable combinations of inputs needed for attaining certain target yields.

SCALE

Geographic scale

The modelling procedure takes no account of geographical scale as it is applied basically as a point analysis. Its application to areas relies on the selection of representative points, followed by spatial aggregation or interpolation. The output of the WOFOST model is intended mainly for national and regional planning, but the procedure can just as well be used at more detailed levels.

Time-scale

WOFOST models one growing season from emergence to maturity. Crop growth and soil water balance are described with a time resolution of one day, and the nutrient uptake is calculated for the whole growing season at once.

CONCEPTS

WOFOST calculates crop yields under three principal growth constraints. This results in three theoretically defined situations that are hierarchically ordered according to increasing analytical complexity. They are:

PS1 Potential production: crop growth is limited by light and temperature regime only. Water and nutrient supply are taken to be optimum.
PS2 Water-limited production: moisture supply may limit crop growth. Nutrient supply is taken to be optimum.
PS3 Nutrient-limited production: the soil nutrient supply is introduced as a growth-limiting factor. Nitrogen, phosphorous and potassium are considered as the most constraining macro-nutrients for crop growth.

Other factors could be introduced such as the influence of weeds, pests and diseases, and the effectiveness of farm operations on crop yields. However, WOFOST does not yet allow for these. With respect to practical farming, PS1 indicates the production ceiling for irrigated farming, PS2 for rainfed farming and PS3 for farming without fertilizer application. PS2 also indicates whether irrigation or drainage is needed to realize a potential yield. Running PS2 for different water management scenarios allows evaluation of their effects on crop yields. Finally, PS3 indicates how much fertilizer should be applied to realize the PS1 and PS2 yields. Actual yields on farms are usually less than calculated theoretical yield. Most farmers in the tropics operate below the PS3 level. The difference in yield may be due to the influence of growth conditions and limitations not considered in the model.

The methodological aspects of the WOFOST model, are comprehensively described by van Keulen & Wolf (1986). The analysis of nutrient-limited production is described in more detail by Janssen *et al.* (1986, 1988). The procedure for the calculation of the CO_2 assimilation rate has been taken from the SUCROS model.

PROGRAM STRUCTURE AND ORGANIZATION OF FILES

The standard microcomputer version of WOFOST comprises source files, data files and executable files (Table 1). WOFOST is divided into modular sections and subsections. This makes it easy to use. Each section corresponds to a FORTRAN subroutine, the subsections are distinguished for editorial convenience only, and their numbers are used in the documentation as paragraph numbers. A summary of all sections is shown in Table 2. The functions of the most important sections are described below. For a detailed program description see van Diepen *et al.* (1988).

Four FORTRAN files WMAIN41, APPLE, NUTRIE and WOSUB are the heart of WOFOST. The first three files correspond with the first three program sections and the file WOSUB is a grouping of the remaining 23 other sections.

The standard data files of the model contain data for 22 crops (mainly tropical), 12 soil types (basically texture classes of the 'Staringreeks'; Wösten, Bannink & Beuving, 1987), and 37 weather stations (situated mainly in the tropics). Table 3 gives a listing of the datasets on file. These data files can be expanded with new data for as many crops, soils or climates as required.

WOFOST is supplemented by three auxiliary programs. All the files are contained on two floppy discs (DS, DD), labelled 'source files' and 'run files', respectively (Table 1).

THE FUNCTIONS OF THE PROGRAM SECTIONS

Section 1 – Program WMAIN41

The flow of the program is organized in the main routine WMAIN41, which allows a single simulation run. In WMAIN41 the user is requested to specify the input data, partly by selecting data from files and partly by typing them on keyboard. Then the input and output files are opened, data are read from the input files through calls to reading subroutines (sections 4, 5, 6), the output control parameters are set and the routines for the calculation of crop yields are called (sections 2, 3).

Section 2 – Subroutine APPLE

The simulation subroutine APPLE (Agricultural Production Potential in Land Evaluation) is basically a crop growth model coupled to a soil water balance model. In the crop growth model, the net daily dry matter increase is calculated as a result of assimilation and respiration. This dry matter is partitioned to the major plant organs: roots, leaves, stems, and storage organs. The rates of these processes and the partitioning pattern are determined by the momentary crop status and its response to controlling enviromental conditions. The crop status for a given day is characterized by model variables such as green leaf area, biomass, and stage of phenological development. The crop growth curve and resulting yield are found by integrating the daily dry matter increase, partitioned to the plant organs, over the total crop growth period.

With respect to the water balance, the user has to choose between simulating with or without groundwater influence in the root zone. The function of the soil water balance is to calculate how much water can be taken from the soil by the crop. This is done on the basis of average water content in the root zone for each day of the growth period. The crop will use less water if the soil is either too dry or too wet. In both situations the transpiration rate is reduced, which leads to a concurrent reduction in assimilation rate. In addition, the soil water balance is interesting for its own sake. Therefore, the daily rates for each term of the soil water balance are cumulated to establish the seasonal balance. Subroutine APPLE calls several other subroutines for the manipulation if climatic data (sections 7, 8, 9) and for calculating of processes (sections 10 through 15).

Table 1. List of files of WOFOST 4.1 on floppy discs

Floppy disc 'Run files'

File name		kbytes	Description
MAKEMENU	EXE	21.6	This command file produces a list of names of available datasets, i.e. file MENU.DAT.
PRNF	EXE	22.9	This command file allows printing of the calculation results in file WOFOST.OUT in an orderly way.
WOFOST	EXE	114.4	This command file allows the interactive use of the WOFOST model.
MENU	DAT	2.3	List of names of available datasets for crops, soils and climates.
SOIL41	DAT	5.3	Physical soil data for 12 soil types (Staringreeks).
CROP41	DAT	23.7	Crop data for 22 crop species or cultivars.
CLIM41	DAT	24.8	Monthly climatic data of 37 weather stations.
REALRD	DAT	7.8	Measured daily rainfall data, to be provided by user. REALRD.DAT requires about 6 kbytes of data for 2 years of rainfall; for 10 years this becomes 20 kbytes.

Floppy disc 'Source files'

File name		kbytes	Description
MAKEMENU	FOR	1.2	
REALRAIN	FOR	1.2	
REALRAIN	EXE	35.6	This command file produces a dummy file REALRD.DAT, filled with zero's for the specified number of years.
PRNF	FOR	1.5	
WMAIN41	FOR	11.1	These four files form together the simulation program of about 92 kbytes long. After compilation of the four files they are linked into one executable file WOFOST.EXE.
APPLE	FOR	31.9	
NUTRIE	FOR	13.6	
WOSUB	FOR	35.1	

Table 2. List of sections (FORTRAN routines) of WOFOST41 and their function

Section	Function	Called by
1 WMAIN41	main program	
2 APPLE	simulation of potential or water-limited production	WMAIN41
3 NUTRIE	calculates nutrient-limited yields and nutrient requirements	WMAIN41
4 SOILRD	reads soil data from file	WMAIN41
5 CROPRD	reads crop or cultivar data from file	WMAIN41
6 CLIMRD	reads climatic data from file	WMAIN41
7 INTERP	calculates daily weather data through interpolation between monthly averages	APPLE
8 RNREAL	reads daily rainfall data from file	APPLE
9 RNGEN	rainfall generator	APPLE
10 PENMAN	calculates daily potential evapo(transpi)ration	APPLE
11 TOTASS	calculates daily total gross assimilation	APPLE
12 RADIAT	calculates the fluxes of photosynthetically active radiation	TOTASS
13 ASSIM	calculates gross assimilation rate	TOTASS
14 ASTRO	calculates day length	APPLE
15 SUBSOIL	calculates capillary rise or percolation	APPLE
16 AFGEN	performs linear interpolation in AFGEN tables	several
17 GAMMA	generates gamma-distributed numbers	RNGEN
18 LIMIT	defines upper and lower limits for certain variables	several
19 RANDOM	random number generator	RNGEN
20 SWEAF	calculates fraction of easily available soil water	APPLE
22 MENU	displays on screen from file MENU.DAT lists of soils, crops and climates available in the data files	WMAIN41
23 PAUZE	requests from user to press 'Return' to continue	several
24 SKIP	skips lines in sequential file	several
25 TABRD	reads data in an AFGEN table	several
26 TEXT	used for output text manipulation	APPLE

Table 3. Datasets in standard data files

WEATHER STATIONS IN CLIM41.DAT		SOIL TYPES IN SOIL41.DAT
BOGRA (006)	BDESH	Medium to coarse sand (05)
CHITTAGONG (306)	BDESH	Fine sand (B1 + 01)
DACCA (009)	BDESH	Loamy fine sand (B2 + 02)
BOBO-DIOULASSO	BFASO	Very loamy fine sand (B3 + 03)
DORI	BFASO	Fine sandy loam (B4 + 04)
OUAGADOUGOU	BFASO	Silt (015)
OUAHIGOUYA	BFASO	Light loam (B7 + 08)
HO	GHANA	Loam (B8 + 09)
KUMASI	GHANA	Heavy loam (010)
NAVRONGO	GHANA	Clay loam (B10 + 011)
TAMALE	GHANA	Clay (B11 + 012)
ABIDJAN	IVOOR	Heavy clay (B12 + 013)
BOUAKE	IVOOR	
KORHOGO	IVOOR	CROPS IN CROP41.DAT
MAN	IVOOR	Barley
TABOU	IVOOR	Cassava
ELDORET	KENYA	Chickpea
GALOLE	KENYA	Cotton
GARISSA	KENYA	Cowpea
KERICHO	KENYA	Field bean
KISUMU	KENYA	Groundnut
KITALE (AIRPORT)	KENYA	Maize
MACHAKOS SCHOOL	KENYA	Millet, bulrush
MOLO PIJR	KENYA	Mungbean
MOMBASA (TOWN)	KENYA	Pigeonpea
NAIROBI (DAG.CORNER)	KENYA	Potato (late cv.)
BAMAKO	MALI	Rapeseed
SEGOU	MALI	Rice HYV-IR8
SIKASSO	MALI	Sorghum
DE BILT	NETHERLAND	Soybean
NIAMEY AERO	NIGER	Sugarbeet
CHANTHABURI	THAIL	Sugarcane
CHIANG MAI	THAIL	Sunflower
KHON KAEN	THAIL	Sweet potato
LAMPANG	THAIL	Tobacco
LOP BURI	THAIL	Wheat, spring
SURAT THANI	THAIL	
CAMBRIDGE	UK	
PARIS	FRANCE	
SCHLESWIG	BRD	

Section 3 – Subroutine Nutrie

Where nutrients limit production it is calculated from the information on uptake of nitrogen, phosphorus and potassium provided by the user and the nutrient concentrations in plant organs and the harvest index resulting from the crop growth simulation. Next, the amounts of fertilizer needed to reach potential and water-limited yields are calculated, making use of the fertilizer recovery fraction (supplied by the user).

Other sections

The names and functions of the sections 4 to 26, all contained in file WOSUB.FOR are given in Table 2. They include routines for reading data from files, for handling data on climate and weather, for calculating rates of CO_2 assimilation and of evapotranspiration, for calculating water flux, and general service routines.

With respect to rainfall, the user may choose between real historical or artificial, mathematically generated daily rain data. The procedure for generating rainfall in routine RNGEN is based on Geng, Penning de Vries & Supit (1986). Each time a call to RNGEN is made, a full year's daily rainfall data is generated on the basis of monthly data. The use of the rainfall generator allows the calculation of time series of water-limited yields and yield variability.

FUNCTION AFGEN (section 13) is used to interpolate between points of a function defined by pairs of values. AFGEN tables consist of up to 15 data pairs.

INPUT PARAMETERS

For a simulation run the user first chooses the crop species, climate and soil type for which the corresponding sets of data are called from standard data files. Then the user must provide some site specific information, such as initial moisture conditions, depth of groundwater, physical properties of the soil surface, and data on soil fertility, which are not included in these files, and specify the starting date (the date of emergence or transplanting).

The standard data files are generally not changed, but of course the user may edit them provided the file structure is maintained.

Climate data
The model uses the monthly climatic data of the CLIM41.DAT file and converts them to daily values for the simulation procedure. The file contains minimum and maximum air temperature, irradiation, humidity, wind speed, monthly rainfall and number of rainy days. Instead of monthly rainfall the user may use daily rainfall from file REALRD.DAT.

Soil profile data
For the simulation of water-limited production only two soil layers (the rooting zone and the subsoil) are distinguished. Variables to be specified by the user are soil type (i.e. soil texture class), maximum rooting depth, and presence of groundwater table with its initial depth.

Soil physical data
The soil physical characteristics defined for each type in the SOIL41.DAT file are: soil moisture characteristics, and soil hydraulic conductivity as function of soil moisture tension. These standard soil data of the 'Staringreeks' are not universally valid and their applicability should be carefully evaluated, at least with regard to the field capacity concept and the amount of available soil moisture. A check on the validity of the standard soil conductivity data is usually difficult because of a lack of measured data. Important properties related to the surface conditions, such as the non-infiltrating fraction of rain and surface water storage capacity, are more site specific and should therefore be specified by the user.

Soil fertility data
Data on soil fertility include the base uptake of nitrogen phosphorus and potassium from unfertilized soil and the recovery fractions of N-, P-, and K-fertilizers. They have to be specified by the user. The base uptake is the nutrient uptake by a reference crop (e.g. maize) with a growth cycle of 120 days. For other crops the base uptake is related to the length of their growth cycle. These data can be derived from detailed fertilizer experiments or estimated from chemical soil data according to the QUEFTS system (Janssen *et al.*, 1986, 1988). Special constraints such as acidity, salinity, toxicities or micro-nutrient deficiencies are not considered in the model.

Crop data
For each crop the CROP41.DAT file specifies the crop data needed for the simulation of its growth. They include initial dry weight, life span of leaves, properties that determine assimilation and respiration rates, rate of phenological development, death rates, fractions of assimilates partitioned to plant organs, and the minimum and maximum nutrient concentrations per plant organ. The length of the growth cycle is the only crop characteristic that can be interactively adjusted by the user.

OUTPUT

WMAIN41 allows the user to modify the output specifications to suit specific requirements. The standard output of the model is shown in Table 4. For a given combination of soil, crop and climate the output is split up by production situation in three parts. The relevant input parameters are shown in the heading of each part.

For the potential production situation, simulation results are given for each tenth day of the growth cycle. The variables listed are dry weights of living leaves, stems and storage organs, leaf area index, development stage, rooting depth, crop transpiration rate, gross assimilation rate, maintenance respiration rate, and total above ground biomass. For the water-limited production situation, the list of crop variables is followed by components of the soil water balance such as actual transpiration and evaporation rates, soil moisture content, surface water storage and amount of water stored in the soil, or groundwater depth. After finishing the simulation of water-limited production, two summarized water balances are given, one for the whole system, and one for the root zone only. Finally, a summary is given of the calculated potential, water- and nutrient-limited yields, harvest indices and fertilizer needs.

LIMITATIONS

Limitations due to model structure
The accuracy of the model is limited by assumptions by simplifying the growth process and by ignoring some of the growth determining factors.

The time-step of one day does not allow a correct simulation of processes having a smaller time resolution, such as water infiltration into the soil, runoff, and the day and night rhythm of the assimilation, respiration and transpiration processes in plants. The same is true for the use of a two layer soil profile, which does not allow the simulation of a moisture gradient within the root zone which reduces the accuracy of the calculations of the rates of evaporation, transpiration and percolation. No growth-limiting factors other than light, temperature, water, nitrogen, phosphorus and potassium are considered, and for the sake of simplicity the interactions between moisture and nutrient supply are not taken into account.

Table 4. Example of standard output of the WOFOST model. The abbreviations are listed in Table 5 (opposite).

WOFOST.OUT/Version 4.1 Last update May 1987 VARP1=1.20 VARP2=1.00

POTENTIAL CROP PRODUCTION

KHON KAEN | THAIL | Maize | Start day 227

DAY	ID	WLV	WST	WSO	LAI	DVS	RD	T	GASS	MRES	DMI	TAGP
227	0	7.	5.	0.	0.03	0.00	10.	0.01	7.9	0.5	5.3	12.
237	10	82.	50.	0.	0.27	0.22	22.	0.05	76.6	4.8	51.1	132.
247	20	659.	404.	0.	1.90	0.44	34.	0.25	385.4	36.3	248.2	1063.
257	30	2045.	1484.	0.	5.32	0.66	46.	0.38	586.9	112.4	335.2	3528.
267	40	3011.	3199.	0.	7.16	0.88	58.	0.41	619.4	179.7	307.9	6366.
273	46	3241.	4333.	125.	7.33	1.00	65.	0.42	624.3	208.6	292.2	8059.
277	50	3288.	4933.	462.	7.23	1.09	70.	0.42	625.3	223.5	283.7	9188.
287	60	3126.	5802.	2205.	6.65	1.31	71.	0.42	616.8	249.1	263.5	11941.
297	70	2942.	5738.	4631.	6.17	1.53	71.	0.40	574.6	258.7	227.4	14420.
307	80	2829.	4688.	6742.	5.88	1.74	71.	0.39	510.8	247.3	189.7	16531.
317	90	1756.	3831.	7879.	3.32	1.94	71.	0.32	174.5	174.5	0.0	17668.
320	93	1382.	3605.	7879.	2.51	2.00	71.	0.27	0.0	0.0	0.0	17668.

SUMMARY:

DAYS	TWRT	TWLV	TWST	TWSO	TAGP	GASST	MREST	HINDEX	TRC	WUSE
46	1590.	3934.	5855.	7879.	17668.	41464.	14391.	0.45	167.	29.6

WATER LIMITED CROP PRODUCTION, Year 1

Start day 227
monthly rain data

KHON KAEN | THAIL | Maize | fixed fraction
Medium to coarse sand (05) | RDMso = 50 | no groundwater | NOTinf = 0.20
SMO = 0.332 SMFC = 0.053 SMW = 0.010 | RDM = 50 | WAV = 3.0 | SSmax = 1.0

DAY	ID	WLV	WST	WSU	LAI	RD	RAIN	T	EVAP	SM	SS	W+WLOW
227	0	7.	5.	0.	0.03	10.	0.0	0.01	0.07	0.053	0.0	2.7
237	10	82.	50.	0.	0.27	22.	7.7	0.05	0.16	0.128	0.4	4.3
247	20	657.	403.	0.	1.90	34.	10.1	0.25	0.03	0.056	0.0	2.8
257	30	2042.	1482.	0.	5.32	46.	16.9	0.38	0.01	0.053	0.0	2.7
267	40	3009.	3197.	0.	7.16	50.	23.4	0.41	0.00	0.050	0.0	2.5
273	46	3240.	4332.	125.	7.33	50.	37.4	0.41	0.00	0.073	0.0	3.7
277	50	3287.	4931.	462.	7.23	50.	42.3	0.42	0.00	0.069	0.2	3.4
287	60	3085.	5735.	1879.	6.54	50.	45.5	0.06	0.00	0.012	0.0	0.6
297	70	2723.	5620.	3390.	5.61	50.	50.6	0.30	0.00	0.021	0.0	1.1
307	80	2188.	4592.	3601.	4.31	50.	51.1	0.03	0.00	0.011	0.0	0.6
317	90	1622.	3752.	3601.	3.02	50.	51.1	0.00	0.00	0.010	0.0	0.5
320	93	1383.	3531.	3601.	2.51	50.	51.6	0.14	0.01	0.017	0.1	0.9

SUMMARY:

DAYS	TWRT	TWLV	TWST	TWSO	TAGP	GASST	MREST	HINDEX	TRC	WUSE
46	1589.	3931.	5735.	3601.	13267.	30405.	9454.	0.27.	152.	20.2

WATER BALANCE WHOLE SYSTEM

irrigation	0.0	evap. water surface	0.0	
rainfall	51.6	evap. soil surface	2.2	
final minus initial:		transpiration	20.2	
-surface storage	0.1	surface runoff	0.9	
-water in rootzone	0.3	lost to deep soil	30.0	checksum: 0.0
-water in lower zone	−2.1			

WATER BALANCE ROOT ZONE

initial water content	0.5	final water content	0.9	
infiltration	50.6	evap. soil surface	2.2	
added by root growth	2.1	transpiration	20.2	
		percolation	30.0	checksum: 0.0

SUMMARY CROP PRODUCTION AND NUTRIENT REQUIREMENTS   Nbas = 15. Pbas = 5. Kbas = 25
Nrec = 0.30 Prec = 0.10 Krec = 0.30

	Potential Crop production	Nutrient limited Crop production	Water limited Crop production
Leaves	3934.	510.	3931.
Stems	5855.	759.	5735.
Storage organ	7879.	729.	3601.
Ratio SO/straw	0.80	0.57	0.37
Harvest index	0.45	0.36	0.27
Fertilizer N	632.3	—	404.3
Fertilizer P	481.0	—	282.1
Fertilizer K	430.5	—	368.3

Table 5. Abbreviations used in the standard of the WOFOST model

Symbol	Description	Unit
VARP	crop variety parameter, indicating the length of the growth period in relation to that of the standard crop	—
VARP1	crop variety parameter for pre-anthesis growth	—
VARP2	crop variety parameter for post-anthesis growth	—
DAY	day number in the Julian calendar, from 1 to 365	d
ID	number of days since emergence	d
WLV	dry weight of living leaves	kg ha^{-1}
WST	dry weight of living stems	kg ha^{-1}
WSO	dry weight of storage organs	kg ha^{-1}
LAI	leaf area index	ha ha^{-1}
DVS	development stage of the crop (0.0 at emergence, 1.0 at anthesis, 2.0 at maturity)	—
RD	effective rooting depth	cm
T	actual transpiration rate	cm d^{-1}
GASS	actual gross assimilation rate of the canopy (in mass units of carbohydrates)	kg $ha^{-1}d^{-1}$
MRES	maintenance respiration rate	kg $ha^{-1}d^{-1}$
DMI	rate of dry-matter increase of the crop	kg $ha^{-1}d^{-1}$
TAGP	total above-ground biomass production, dry weight of living and dead plant organs	
DAYS	number of days since emergence to anthesis and to maturity, respectively	d
TWRT	total dry weight of roots (dead and living)	kg ha^{-1}
TWLV	total dry weight of leaves (dead and living)	kg ha^{-1}
TWST	total dry weight of stems (dead and living)	kg ha^{-1}
TWSO	total dry weight of storage organs	kg ha^{-1}
TAGP	total above-ground dry weight (dead and living)	kg ha^{-1}
GASST	total gross assimilation, in carbohydrates	kg ha^{-1}
MREST	total maintenance respiration	kg ha^{-1}
HINDEX	harvest index	
TRC	transpiration coefficient (ratio of water use and dry matter production)	kg kg^{-1}
WUSE	water use, or total transpiration during growth cycle	cm
RDMso	maximum rooting depth allowed by the soil	cm
NOTinf	non-infiltrating fraction or rainfall	—
SMϕ	soil moisture content at saturation	cm cm^{-3}
SMFC	soil moisture content at field capacity	cm cm^{-3}
SMW	soil moisture content at wilting point	cm cm^{-3}
RDM	maximum rooting depth	
WAV	initial amount of water in total rootable zone (amount of water above wilting point)	cm
SSmax	surface storage capacity	cm
RAIN	total rainfall since crop emergence	cm
T	actual transpiration rate	cm d^{-1}
EVAP	actual evaporation rate from soil or water surface	cm d^{-1}
SM	soil moisture content in root zone	cm^3 cm^{-3}
SS	surface storage, depth of water layer	cm
W+WLOW	amount of water in rootable zone	cm
W	amount of water in rooted zone	cm
WLOW	amount of water in rootable zone below the momentarily rooted depth	cm
Nbas	actual supply of nitrogen from the soil during the crop growth period	kg ha^{-1}
Pbas	actual supply of phosphorus from the soil	kg ha^{-1}
Kbas	actual supply of potassium from the soil	kg ha^{-1}
Nrec	recovery fraction of applied fertilizer nitrogen	—
Prec	recovery fraction of applied fertilizer phosphorus	—
Krec	recovery fraction of applied fertilizer potassium	—

Limitations due to data constraints
Despite the simplifications, the model still requires many data, and the general scarcity of data seriously limits its use as a predictive tool in land evaluation and for planning. For instance, a simulation run of water-limited production requires more soil physical data than a routine soil survey can provide. Moreover, many of the environmental data used pertain to average conditions and do not allow the evaluation of the effects of their erratic nature and of extreme conditions. The data constraint is also a problem for the further development of the model because complete and detailed datasets are needed for model validation. Such datasets may be either measured experimental data or data generated by more detailed, validated models. However, very few datasets appear to be available.

COMPUTERS AND PROGRAM LANGUAGE

WOFOST can be implemented on any IBM-PC or IBM-AT compatible machine using an IBM FORTRAN compiler. After a few changes WOFOST can also be implemented on a VAX/VMS system using a FORTRAN77 compiler. The FORTRAN is as general as possible to allow implementation on other machines with a minimum of program modifications.

ASSOCIATED SYSTEMS

Geographic Information System
A Geographic Information System (GIS) is used for the construction of a geographic data base. This allows soil and climate maps to be digitized. The GIS provides the facilities to input, combine, extract and display spatial data. The GIS can be used to select all unique soil–climate combinations in a country. These can be sent to the WOFOST model to run simulations for all combinations for a given crop and to produce country maps of calculated yield levels for that crop. This procedure has been followed for the calculation of water-limited yields and yield variability of maize in Zambia by Wolf, van Diepen & Immerzeel (1987). The maize yield variability shown in Fig. 1 is based on simulated yields over 20 years for each soil–climate combination and is calculated as the coefficient of variation.

Agro–economic model
The yield levels generated with the WOFOST model are accompanied by the amount of inputs required for actually achieving these yields. These yield and input data can be used in a linear programming model for agricultural production in a region, to establish regional production potentials under a given set of socio–economic constraints. Such an approach can be applied in land-use planning (van Keulen *et al.*, 1987).

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