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Proposition of PhD Dissertation

Evaluation of crop production parameters in a long-term tillage experiment by Ceres Maize Simulation Model v. 3.5

by

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1. Introduction

During the last years scientists have shown greater and greater interest in using crop models. By spreading decision support systems agricultural decision makers at all levels also apply methods for simulating processes of soil-plant-atmosphere systems (KOVÁCS, 1995). Crop models simulate crop growth and development, environmental (atmosphere and soil) processes as well as agricultural practices for daily increment. If crop model is validated on a specified crop-environment system, all important parameters during growing season can be controlled and the effect of modified crop production practices can also be determined. By using crop models years can be generated, the effects of fertilization, tillage, irrigation, plant density and crop rotation can be examined and production strategies on yield, net income and environmental effects can be evaluated.

Simulation system models are also designed to understand the operation and the development of a particular ecological system and to find the missing links of our knowledge about them. During development of a model it often turns out that several important parameters of yield and environmental effects and interactions between them are not measured or observed. These aspects give experimental researches a stimulus again and again (Kovács, 1995). The cost of several field experiments can be saved if multipurpose simulations are performed before setup of experiments. With the help of model calculation and strategic analysis hypotheses are created concerning optimum technologies. It is worth mentioning that field experiments cannot be replaced with simulation models. However, our original plan can be modified before experimentation by means of these simulation models and experiments will be carried out in the optimum combination of treatments. Consequently, simulation reduces the duration of experiments i. e. it makes experiments cheaper, faster and more efficient.

The methods mentioned above demand further improvement before their regional extension and field adaptation. Database of the long-term tillage experiment carried out at the research station of Centre for Agricultural Sciences of Debrecen enables to observe crop models concerning the effects of grain yield, biomass and some crop production parameters (tillage, fertilization and plant density), moreover it helps to understand the relationship between a plant and its environment better.

During the researches at the university the model has already been adapted on several fields. By means of the model the effects of crop production parameters on corn yield and seasonal dynamics of soil water and nutrient supply were analyzed. The aim of this study beyond these experiments was to make validation of Ceres-Maize model complete evaluating not only corn yield but also the most important characteristics of corn growth and development. The further goal of my work were the following:

- to study corn growth and development and interactions of soil-plant-atmosphere systems,
- to determine initial soil parameters, plant densities required for simulation and genetic coefficients of hybrids,
- to analyze parameters of growth and phenological development of maize genotypes in different treatments of fertilization, plant density and tillage; to simulate corn yield and the most important growth and development parameters during growing season,
- to observe confidence of Ceres-Maize simulation model v. 3.5 and to adapt it with the help of the database of Centre for Agricultural Sciences.

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2. Materials and methods

2.1. Main characteristics of tillage experiment

The three-year research was carried out in a polyfactorial long-term experiment set up by Professor János Nagy from 1997 to 1999 at the experimental station of the Department of Land Use, University of Debrecen located at Látókép.

Since 1983 the main goal of experiments has been to evaluate the effects of fertilization, tillage, plant density and irrigation on yield of maize hybrids (Nagy, 1996). By means of crop models corn growth and soil-plant-atmosphere interactions can also be examined. Database of the long-term experiment forms the input of Ceres-Maize and other simulation models contributing to their regional adaptation.

The long-term experiment was set up in split-split-plot arrangement. In the main blocks different tillage and irrigation treatments were applied without replication. In the prime sub-blocks maize hybrids were sown at a plant density of 50-70-90 000 respectively, in the secondary sub-blocks treatments of fertilization were set up in a random block with four replications. The size of each tillage block was 8 064 m^2 splited into an irrigated and a non-irrigated block. The size of each main block, in which one maize hybrid was sown, was 2 688 m^2. The size of fertilization blocks was 336 m^2 and net area of a block was 15.2 m^2.

Tillage treatments were winter plowing to a depth of 27 cm, spring plowing to a depth of 23 cm and shallow spring disk tillage to a depth of 12 cm. Fertilizers were applied at a rate of 120 kg ha^{-1} N, 90 kg ha^{-1} P, 106 kg ha^{-1} K and 240 kg ha^{-1} N, 180 kg ha^{-1} P, 212 kg ha^{-1} K. Since 1997 crop rotation of wheat and maize has been set up in 50-50 % of the area of spring plowed and disk-tilled plots. In the biculture maize hybrids were sown at a plant density of 70 000.

2.2. Soil characteristics of the examined area

The experimental station is located at the north-eastern part of the Great Hungarian Plain (Hajdúság), the type of its soil is lowland pseudomiceliar chernozem (Mollisol-Calciustoll or Vermustoll, silt loam; USDA taxonomy). Main physical and chemical characteristics of the soil profile are shown in **Table 1 and 2**.

Table 1. **Main physical characteristics of soil**

depth	saturated percentage	K_A	higroscopocity	bulk density	porosity	DUL	LL
cm	Li %	K_A	hy	g cm^{-3}	P %	%	%
0-20	56.8	42	2.25	1.41	46.7	33.7	12.69
20-40	58.6	43	2.25	1.43	46	31.1	12.87
40-60	57.1	43	2.13	1.31	50.5	29.1	11.16
60-80	57.5	44	2.51	1.29	51.3	28.6	12.51
80-100	58.6	48	2.07	1.30	50.9	29.1	10.76
100-120	54.1	47	2.18	1.24	53.3	27.4	10.81
120-140	55.3	46	1.91	1.24	53.3	27.8	9.47

Table 2. **Main chemical characteristics of soil**

depth	acidity(pH)		$CaCO_3$ content	humus content	total N%	AL-soluble	
						P_2O_5	K_2O
cm	H_2O	KCl	%	%	%	ppm	
0-20	7.3	5.6	0	2.72	0.150	133.4	240.0
20-40	7.2	5.4	0	2.31	0.120	48.0	173.6
40-60	7.2	5.8	0	1.68	0.100	40.4	123.0
60-80	8.0	7.2	1.1	1.02	0.086	32.4	96.5
80-100	8.4	7.5	11.6	0.81	0.083	39.8	93.6
100-120	8.4	7.5	10.6	-	-	40.6	86.1
120-140	8.4	7.5	7.5	-	-	31.6	78.0

2.3. Weather characteristics

The amount of daily rainfall was measured at the experimental station. Data of daily solar radiation, minimum and maximum air temperature were made available for us by the Department of Mathematics, Physics and Agrometeorology, University of Debrecen. Weather conditions from 1997 to 1999 were favourable to maize development. In 1998 and 1999 there was a rare coincidence: both of these years were more rainy than the average years and deviation of mean air temperature in growing season was also positive. In these years not only the more precipitation, but increase of temperature could also contribute to yield growth. Maize development was not hindered by either drought or cool weather.

2.4. Evaluation methods used in the research

2.4.1. General characteristics of simulation model

Simulation was carried out with Ceres-Maize simulation model v. 3.5 (JONES and KINIRY, 1986; RITCHIE et al., 1994). Simulation model is one of the most important components of the DSSAT (Decision Support System for Agrotechnology Transfer). This system enables to store and demonstrate results of the runs graphically. Schematic of the main components of the DSSAT and Ceres-Maize model are shown in **Figure 1**.

Ceres-Maize model belongs to the group of so-called deterministic models. It is designed to simulate crop development, biomass accumulation, leaf area, assimilation, distribution of assimilates in plant organs, root depth and root length density in soil layers, soil water movement, evapotranspiration, nitrogen transformation and movement in soil and plant nitrogen uptake and distribution.

Ceres-Maize model is a robust model i.e. it does not consider those unimportant factors which enhance possibility of errors. It gives a general outline of processes of soil-plant, atmosphere systems and endevours to operate simply and proportionally. It takes plants as a basis and simulate processes for daily increment and in capacitive way (e.g. field water capacity of soil layers forms the basis of the model of water movement). The model also requires daily weather data and gives daily results. The unit area, which is considered homogenous by the model, is the growing area of a plant. Thus the model takes only one plant into account and describes its environment during simulation process. The computer program is written in the familiar scientific language, FORTRAN and developed to run a year. However, certain years can continously be run with the help of seasonal analysis. In this case output files of the previous year will be the input parameters of the next year (Ritchie et al., 1994).

Figure 1. **Schematic of the main components of the DSSAT v. 3.5**

2.4.2. Input and output files of Ceres-Maize model

The following input files are required to run the program: daily weather data including minimum and maximum air temperature, precipitation and solar radiation; soil data including the detailed description of soil profile; genetic data including genetic parameters of maize hybrids applied in the experiment; measured experimental data and files of technological parameters. Output files contain simulation of plant growth, weather, soil water and nutrients as well as nitrogen and water balance. The files of the model were summarized in **Table 3**.

Table 3. **Input and output files of Ceres-Maize model**

Input files	Output files
daily weather data (*.*wth*)	general output file (*overview.out*)

soil data (*soil.sol*)	plant growth data file (*growth.out*)
genetic parameters (*mzcer980.cul*)	weather and soil water output files (*water.out*)
experimental data (**.mzx*)	nutrient output file (*nitrogen.out*)
data measured at harvest (**.mza*)	water balance (*watbal.out*)
data of seasonal measurements (**.mzt*)	nitrogen balance (*nbal.out*)

The most important physical and chemical characteristics of soil were given at layers. 10 layers were distinguished in the soil profile to a depth of 2 m. The maximum thickness of a layer was 30 cm and the maximum number of layers was not more than 15. The main input soil parameters required to run the model are shown in **Table 4**.

Table 4. **Input soil files required to run the model**

	Winter plowing				Spring shallow disk tillage			
Layer	LOL	DUL	SAT	BD	LOL	DUL	SAT	BD
cm	cm^3 cm^{-3}	cm^3 cm^{-3}	cm^3 cm^{-3}	g cm^{-3}	cm^3 cm^{-3}	cm^3 cm^{-3}	cm^3 cm^{-3}	g cm^{-3}
0-5	13.0	31.4	47.9	1.38	12.5	30.3	49.8	1.33
5-15	13.0	32.2	46.4	1.42	14.8	34.0	38.9	1.62
15-30	13.0	32.8	45.3	1.45	12.5	31.6	47.5	1.39
30-45	12.9	29.5	51.3	1.29	13.7	31.2	48.3	1.37
45-60	12.7	28.5	53.2	1.24	13.6	30.3	49.8	1.33
60-90	10.8	28.7	52.8	1.25	10.8	28.7	52.8	1.25
90-120	10.2	27.7	54.7	1.20	10.2	27.7	54.7	1.20
120-150	10.3	27.9	54.3	1.21	10.3	27.9	54.3	1.21
150-180	12.3	28.3	53.6	1.23	12.3	28.3	53.6	1.23
180-200	14.0	28.7	52.8	1.25	14.0	28.7	52.8	1.25

In **Table 4** the value of LOL is the lower limit of plant extrable water, the value of DUL is the drained upper limit and the value of SAT is water content at saturation. BD means moist bulk density, which is based on the volume of swelling clay minerals.

The genetic parameters of maize hybrids applied in the experiment are presented in **Table 5**. The variable of P1 is growing degree days (GDD) (base 8 °C) from seedling emergence to the end of the juvenile phase(˚C d), P2 is photoperiod sensitivity measured in days of tassel initiation delay per hour of photoperiod increase (d h^{-1}), P5 is the daily thermal time from silking to physiological maturity (˚C d), G2 is potential kernel number (kernel cob^{-1})˚C day) and G3 is potential kernel growth rate (mg d^{-1} $grain^{-1}$).

Table 5. **Genetic parameters used during the model run**

Hybrids	P1	P2	P5	G2	G3

Debreceni 377 SC	145	0.5	750	750	7.25
DeKalb 471 SC	185	0.5	775	830	7.20

2.4.3. Evaluation methods of crop growth and development

The multifactorial long-term tillage experiment was carried out on lowland pseudomiceliar chernozem soil (Mollisol-Calciustoll or Vermustoll, silt loam; USDA taxonomy) and the samples were collected from *non-irrigated plots*. Two single-cross maize hybrids with different maturity, *De 377 SC* (FAO 340) and *Dk 471 SC* (FAO 410) were sown. Tillage treatments were *winter plow to a depth of 27 cm* and *spring shallow disk tillage to a depth of 12 cm*. In 1998 and 1999 experiments were performed on plots *without fertilization* and with a rate of *120 kgha^{-1} N, 90 kgha^{-1} P and 106 kgha^{-1} K*. In 1997 fertilizers were only applied at a rate of *120 kgha^{-1} N, 90 kgha^{-1} P and 106 kgha^{-1} K*.

Maize hybrids were sown at a plant density of *50 000* and *70 000* during the three years. Samples were taken from the 4-6 leaf stage of corn until its physiological maturity (recommended by Hanway, 1962). Hanway divided phasic development of maize into 10 stages compared to seedling emergence. Phases before silking were established on the basis of number of leaves while phases after silking were determined on the basis of kernel growth.

From each treatments and replications 3 plants were removed and were separated into stem, tassel, sheath, leaf, husk, cob and kernels and dried to constant weight at 60 °C. Change of above-ground biomass and grain filling were measured from silking to physiological maturity. To calibrate the model potential kernel growth rate (G3) was calculated in 1998. For this reason further details of grain filling were determined. From silking to the end of the linear phase of kernel growth samples were taken at 5-6 day intervals.

Dry weight of corn yield and its mean components (kernel number m^{-2} and cob^{-1}, kernel weight and plant density at harvest) were also examined. The aim of phenological measurements was to describe seedling emergence, silking and tasseling and physiological maturity (appearance of black layer). Further details of each phenological phase were determined every second or third day. The maximum length and width of leaves were measured at the time of biomass sampling. Leaf area of individual plants and leaf area index were calculated by means of Montgomery-formula measuring the length and width of leaves (Montgomery, 1911).

2.4.4. Evaluation methods of soil characteristics

In order to determine *soil water content* samples were taken in spring before sowing (on 28th March 1997, 24th April 1998 and 15th April 1999) in 3 replications from winter-plowed and disk-tilled plots without fertilization and with a rate of 120 kgha^{-1} N, 90 kgha^{-1} P and 106 kgha^{-1} K. (In 1997 samples were only collected from fertilized plots.) Measurements were carried out in a soil layer of 0-200 cm and 10 layers with different thickness (0-5, 5-15, 15-30, 30-45, 45-60, 60-90, 90-120, 120-150, 150-180, 180-200 cm) were identified in it. The moisture content of the soil were gravimetrically determined from disturbed samples.

Samples taken to determine soil water were also used to observe *nutrient supply*. NH_4-, NO_3-N, P_2O_5 and K_2O content of the soil were measured by Sample Examination Centre, University of Debrecen.

The *bulk density of soil* was determined from undisturbed soil samples gathered in the first part of the growing season and at harvesting in 1997 with cartridge sample taking method.

2.4.5. Analysis of research results

Statistical evaluation was done with SPSS for Windows 8.0 software and on the basis of Sváb's reference book (Sváb, 1991). *Multifactorial variance analysis* was applied to test the effects of different crop production parameters separately. These parameters were the following: *seedling emergence, silking, physiological maturity, individual crop yield, biomass, kernel number, kernel weight, leaf area index and plant density*. With the help of multifactorial variance analysis treatments can be compared and distinguished more accurately.

In the course of model validation, verification and adaptation *linear regression model* was used to describe relationships between measured and estimated data. Observed data were the independent variables of regression and predicted results were the dependent variables of it. During the regression process measured and predicted data of 1997 and 1999 were analyzed. Because data of 1998 were used to calibrate the model, results of this year were not independent Experimental data were evaluated and texts, figures and tables of my work were prepared with Microsoft Office Excel 5.0 and Word 7.0 programs.

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3. Results and discussions

3.1. Results of measurements concerning initial soil water and mineral nitrogen

The amount of soil water in spring of 1998 and 1999 provided optimum initial conditions for maize growth and development in both tillage and fertilization treatments. In 1998 soil water before sowing was not significantly decreased by fertilization and the effects of tillage treatments carried out at different soil depths and points of time were not significant either in 1998 or 1999. In 1997 germination and seedling emergence were delayed by low water content of the surface layer about 0-10 cm deep in both tillage treatments.

On the basis of simulation soil water content in spring could be quite accurately predicted in the upper 60 cm layer with the help of the model. However, measured values in layers deeper than 60 cm were considerably underestimated. Reasons for the difference is that the model does not consider the effect of excess water soaking from the surrounding soil layers into the layer 2 m thick.

On the grounds of our results it was established that the amount of any nitrogen forms in the soil profile was not remarkable without fertilization. Nitrogen forms were evenly distributed and their amount from the surface to the deeper layers notably decreased. The amount and distribution of mineral nitrogen forms were not influenced by tillage treatments without fertilization. Mineral nitrogen supply of the soil in fertilized plots was also not considerably affected by tillage treatments carried out at different soil depths. This value in disk-tilled plots was lower with 30-50 % than it was in plowed plots. According to the results of simulation NO_3-N was not leached out from the observed soil layers in any treatments, however denitrification exceeded the amount of the applied fertilizers with 30 %. Considerable nitrogen losses could be attributed to the heavily compacted layer in the 15-20 cm soil profile and waterlogged soil conditions caused by soil water content exceeding the value of field capacity.

3.2. Effects of soil tillage on individual crop yield and plant density

From 1997 to 1999 individual crop yield was only increased significantly by fertilization and plant density and there was not a considerable difference between tillage treatments. According to our observations individual crop yield in years with appropriate weather and much rainfall was not decreased accurately in spite of shallow disk tillage treatment. Standard deviation of individual crop yield was not influenced considerably by any treatments. Neither tillage treatments nor the rate of fertilization and different plant densities caused consistently less or more heterogeneity in corn stand. The established standard deviation differences were chance occurences and could be explained by sample taking errors.

On the basis of measurements plant density was notably affected by different tillage treatments. The observed plant density in winter plowing was roughly corresponded with the calculated number of emerged plants i.e. the 95 % of estimated field emergence. In shallow disk-tilled treatments decrease of plant density at harvesting was less or even less than 15 %. Corn stand was also inconsistent in the case of disk-tilled plots. There was statistical difference between plant densities of the two tillage treatments only in 1997 and

1998 and was caused by great variability of plant density. Low and very different plant density of disk-tilled plots can be explained by soil surface covered with clods and crop residues. Inadequate soil surface not only delays simultaneous and fast seedling emergence but also makes sowing more difficult.

3.3. Determination of genetic coefficients used by the model

The first step of model adaptation is calibration, the accurate setup of phenological phases and crop development parameters. The aim of calibration is to determine exactly genetic parameters used in the model. Parameters of new genotypes applied during the model run are generally not published, thus these factors are set up on the basis of field experiments.

To determine model parameters results of measurements in 1998 and sensitivity test were used. These parameters were applied without modification in each treatment during model run and validation. In the course of sensitivity test only one parameter was modified but other parameters were not. P1 and P5 genetic coefficients were changed until there was a match between the observed and simulated dates of phenological characteristics.

Determination of P2 parameter were carried out similarly. On the basis of our observation it was established that hybrids applied in the field experiments were moderately sensitive to the length of the day, therefore the value of P2 coefficient was adjusted to 0.5.

Potential kernel growth rate (G3 coefficient) was determined at a plant density of 50 000, because it provided optimum conditions to dry-matter accumulation. In the case of both hybrids grain growth rate could be described with a logistic curve. The slope of the line adjusted to the linear phase of this function gives G3 parameter, the maximum daily kernel growth rate.

Potential kernel number (G2) was estimated from samples taken 1-2 weeks after silking from fertilized plots with a seeding rate of 50 000. This parameter could be considerably decreased by higher plant densities and lower rates of fertilization. Potential kernel number observed in growing season was not influenced by tillage treatments. However, kernel numbers during this period were different in each treatment. These factors notably decreased to the beginning of the intensive phase of grain filling and it remained constant to the end of the growing season.

3.4. Evaluation of Ceres-Maize simulation model v. 3.5

Essential part of simulation and crop model development is to determine its accuracy in predicting the observed phenomena. Before applying the model in simulation it should be calibrated with the help of field experimental data. The second step in the evaluation of the model is validation by which the model can be verified for a specific experimental site. In the course of validation simulated results are compared with observed data and relationship are searched by means of linear regression model based on minimum sums of squares of deviations of predictions from observation.

3.4.1. Simulation of the dates of maize phenological stages

In 1997 delayed and uneven seedling emergence was recorded which could be explained by low water content and poor quality of the seedbed in both tillage treatments. In disk-tilled treatments emergence was also delayed by a large amount of above-ground crop residues. There was a considerable difference between the observed and estimated dates of emergence in both tillage treatments. Comparing with measured values the date of emergence was predicted 6 and 9 days earlier in winter plowed and disk-tilled plots respectively. In 1998 and 1999 environmental conditions had favourable effects on seedling emergence of corn hybrids and simulated values in both tillage treatments corresponded well with measured data.

Depending on the tillage treatments and hybrids the model predicted the date of silking 7-10 earlier in 1997. The error of prediction can be explained by delayed germination and seedling emergence (caused by low soil water content). In 1998 and 1999 the model simulated accurately the date of silking of both hybrids;

predicted values were approximately similar to measured data in shallow disk tillage treatment.

Comparing the observed data with the simulated values in 1997 the model systematically underestimated the date of physiological maturity with about 7-10 days similarly to the dates of emergence and silking in all treatments of both hybrids. In the following two years it predicted accurately the observed data.

According to the results of measurements the model predicted accurately the date of seedling emergence, silking and physiological maturity if there were optimum soil and weather conditions for germination and initial maize development. If these conditions are not existed the model simulated more inaccurately phenological parameters. Reason for this mainly is that the date of germination is determined by water content of soil layer containing sown seeds and layers lying underneath. But the average water content of these layers are not sufficient to estimatethe date of germination accurately. Other important factors such as soil conditions surrounding the seed, roughness of seedbed, spatial distribution of soil water, surface of the seeds, relationship between soil particles, the amount of crop residues, the way and the date of tillage treatments are not considered by the model.

3.4.2. Evaluation of the most important variables of maize growth and development

3.4.2.1. Simulation of grain yield

In 1997 the model in all treatments consistently underestimated grain yield of corn hybrids. It was caused by delayed sowing and silking which were simulated with great error. In 1998 the model predicted well the effects of tillage, fertilization and plant density. Deviations between the measured and simulated values were in the range of standard deviation or approached it in all treatments. The accuracy of prediction was higher in shallow disk-tilled plots. The measured grain yields were also simulated very accurately by the model in 1999. The model determined precisely the deviations among each treatment. These deviations were not higher than the calculated standard deviation.

Significant relationship ($p = 1.45*10^{-6}$) was found between simulated and measured data (**Figure 2**). In the regression equation BE means simulated grain yield and ME is measured grain yield. The value of r^2 was 0.66 and the regression line had a slope of 0.88 with a Y-intercept of 174.9 kg ha^{-1}. On the basis of the t-test regression coefficient was significantly different from zero i.e. grain yield was sistematically underestimated by the model. Residual standard error was 1287.9 kg ha^{-1} (13.8 % of the average). In **Figure 2** data points of 1999 were fairly distributed around the 1:1 line.

3.4.2.2. Simulation of grain yield components

One of the most crucial points of modelling is to determine grain yield components (kernel number per ear and kernel weight) accurately, because these parameters are often over- or underestimated by Ceres-Maize model.

The model predicted *kernel number* with different accuracy in all years. Comparing with the measured data it underestimated kernel number of De 377 SC and Dk 471 SC with 16-20 % and 31-38 % respectively. In 1998 there was not a considerable difference between the predicted and observed values. The average deviation was not higher than 10 % at a plant density of 50 000, however the standard error of estimation increased to 13-15 %. The model simulated the observed kernel number with the same accuracy in both tillage treatments. In 1999 measured results corresponded with predicted data except the values of plots without fertilization. In these plots kernel number was underestimated with 22-29 % (De 377 SC) and 23-45 % (Dk 471 SC). High standard error of estimation can be explained by low nutrient supply of plots without fertilization.

Significant relationship ($p = 3.2*10^{-5}$) between simulated and observed data was described by the following regression equation:

ES = 1.13 ME – 200.9, whereby ES is predicted kernel number, ME is measured kernel number.

Determination coefficient (the r^2 value), which gives the fitting of regression line, was average ($r^2 = 0.55$) and the standard error was high (15.2 % of the average). The Y-intercept was significantly different from zero i.e. the model sistematically underestimated kernel number similarly to grain yield (**Figure 2**).

In contrast with predicted kernel number simulated *kernel weight* was not significantly different from the measured data in 1997, the standard error of estimation was within 5 %. In 1998 observed data were accurately predicted (with 5-7 % standard error on average). In 1999 the standard error of estimation was higher than 20 % in treatment without fertilization i.e. simulated values comparing with calculated kernel weight were greater with approximately 25-71 %.

In 1997 and 1999 measured and simulated data were analyzed by means of linear regression. In these years there was not a significant relationship between them. The r^2 value also indicated that regression line could not be accurately fitted to data points. The reason for this was that the values of kernel weight measured in treatments without fertilization were simulated inaccurately. Simulated values were sistematically greater than observed data in the range of 220 mg kernel $grain^{-1}$.

To sum up it can be stated on the basis of measured and predicted grain yield components that the model simulates both parameters (kernel number and kernel weight) in relatively limited domain. In 1997 low simulated grain yield was mainly caused by small predicted kernel number and not by kernel weight. In 1999 simulated and measured grain yields corresponded well with each other, but it can be explained by the underestimation of kernel number and the overprediction of kernel weight.

3.4.2.3. Simulation of biomass

In 1997 measured and predicted biomass were also significantly different. The model underestimated dry weight with approximately 18-24 % (De 377 SC) and 25-39 % (Dk 471 SC). In 1998 and 1999 the standard error of estimation was within 5 % in De 377 SC and 5-10 % in Dk 471 SC.

Significant relationship ($p = 2.53*10^{-12}$) between simulated and observed above-ground biomass was described by the following equation:

ES = 0.73 ME + 2621.3, whereby ES is predicted weight of biomass and ME is measured weight of biomass. On the basis of the r^2 value ($r^2 = 0.69$) the fitting of regression line was average, while the standard error was 8.8 % of the average, 1683 kg ha^{-1} (**Figure 2**).The Y-intercept was significantly different from zero, consequently the model sistematically underestimated the values of biomass. Data points were fairly distributed around 1:1 line. They were most distributed in the domain of 14-20 t ha^{-1}, which can be explained by the underestimation of biomass measured in 1997. In 1997 measured and predicted above-ground biomass was 14400-20580 kg ha^{-1} and 11299-15083 kg ha^{-1} respectively.

3.4.2.4. Simulation of harvest-index (HI)

In 1997 measured harvest-index corresponded well with simulated harvest-index of De 377 SC. It was caused by similar underestimation of biomass and grain yield. Predicted HI of Dk 471 SC in 1997 was less with 4-7 % than measured HI. On the basis of these the model predicted grain yield components with higher accuracy. In 1998 and 1999 there was not a significant difference between the simulated and measured HI of De 377 SC. The standard error of estimation was only 1-3 %. In the other two years predicted HI was higher with approximately 3-10 % than measured values, however the standard error of estimation exceeded the 10 % at a plant density of 50 000 in plots without fertilization. Consequently the model simulated more inaccurately in the case of Dk 471 SC. It was also supported by lower predicted above-ground biomass.

With the help of linear regression significant relationship ($p = 1.24*10^{-6}$) was found between measured and predicted HI values (**Figure 2**). It could be accurately described by linear regression equation. Residual standard error was 0.03 kgha^{-1} (5.6 % of the average). The fitting of regression line was average (r^2 = 0.66), which was shown by the distribution of data points around 1:1 line. Distribution of these points around 1:1 line was even only in the domain of 0.5-0.54 kg kg^{-1}. The model simulated inaccurately both higher (<0.5) and lower (>0.54) HI values and under- and overestimated the measured results. In contrast with the measured HI of Dk 471 SC (0.446-0.558 kg kg^{-1}) simulated values were in the domain of 0.429-0.651 kg kg^{-1}.

3.4.2.5. Simulation of maximum leaf area index (LAI_{max})

Simulated LAI_{max} values of De 377 SC and Dk 471 SC were accurately lower with 18-30 % and 21-26 % respectively than measured results. In 1998 the model overpredicted the observed data with 5-10 %. In 1999 the simulated LAI_{max} of De 377 SC was higher with 10-13 % on average than the measured values. However, the LAI_{max} of Dk 471 SC were simulated with great accuracy. The standard error of estimation was within 5 % on the basis of linear regression and data points in 1998 and 1999 were fairly distributed in spite of their overprediction, while the LAI_{max} values in 1997 were sistematically underestimated by the model (**Figure 2**).

Figure 2. **Relationship between observed and simulated variables of maize growth and development (1997, 1999)**

3.4.3. Evaluation of the seasonal changes in the measured and simulated dry matter accumulation

In 1997 the fitting of the curves demonsrating simulated data was good only in the case of the biomass values determined at the time of the first and second sample taking and then the results of field measurements in all treatments were estimated with greater and greater error. In spite of the considerable standard error of estimation differences in dry matter accumulation were accurately described by the slope of simulation curves in disk-tilled plots. The above-ground biomass of the observed hybrids in disk-tilled plots was less also on the basis of the model run.

Biomass values measured in the growing season of 1999 were accurately adjusted to simulation curves. Between the measured and predicted values there were not considerable differences. It was also proved by the curves of tillage treatments that different tillage treatments did not have an effect on dry matter accumulation in the case of good nutrient supply of soil and favourable weather conditions.

To sum up it can be stated on the basis of measured and simulated data of 1997 and 1999 that the model estimates total above-ground biomass of maize and seasonal dynamics of dry mater accumulation in all treatments with appropriate accuracy if environmental conditions are favourable. Since roughly similar biomass values were measured (except the values of disk tilled plots) in the growing season of both observed years, further simulations are needed to find the causes of the considerable standard error of estimation in 1997 out.

3.4.4. Evaluation of the seasonal changes in the measured and simulated leaf area index (LAI)

In 1997 the model consistently underestimated the leaf area of maize with approximately 25-35 % depending on tillage treatments. The values of LAI_{max} compared to measured data were predicted 6-8 days earlier in all treatments.

In 1999 there was not a considerable difference between the measured and predicted data of any genotypes. Simulation curve was closely fitted to measured data points, difference tillage treatments and plant densities were accurately estimated by the model.

According to the results of measurement in 1997 and 1999 LAI and seasonal dynamics of leaf area in maize can be simulated with appropriate accuracy by means of the model in the case of optimum weather and environmental conditions. In contrast with the similar values of LAI in the growing season of both years the causes of the considerable standard error of estimation in 1997 are required to reveal with the help of simulation experiments.

3.4.5. Simulation experiments carried out with Ceres-Maize model v. 3.5

With the help of simulation experiments it was tried to explain problems arisen during the evaluation of the results in 1997. Weather data of critical stages (sowing – tassel initiation, grain filling) of maize growth and development in 1997 were replaced by the values of 1999. The model run was performed with modified weather database leaving initial parameters such as soil water, nutrient supply, bulk and plant density unchanged, and the effects of correction on charactersitics of maize growth and development were analyzed.

Owing to low temperature the dates of predicted seedling emergence were delayed in modified versions, thus the dates of simulated values were exactly identical with the ones of measured data in 1997. Consequently, the predicted date of emergence was only influenced by temperature in addition to sowing depth. High temperature of the period from sowing to seedling emergence results in too early and inaccurate estimation of field emergence if soil conditions (roughness of seedbed, soil water content) are not suitable for germination.

In the modified versions of the model run the dates of silking and physiological maturity as well as maximum leaf area index were accurately simulated by the model. It is closely connected with the problem that maximum leaf number is increased and the date of silking is delayed by high temperature measured directly before tassel initiation and in the inductive phase. Thus the predicted leaf number and the values of LAI_{max} in 1997 were decreased by low temperature recorded in the critical inductive phase and the simulated date of silking got earlier.

According to our measurements the rate of dry matter accumulation and the amount of biomass in 1997 were not limited by water and nutrient supply, but they were limited by extremely low values of solar radiation and temperature measured in the initial and intensive phase of grain filling. Besides there were not direct relationships between phenological parameters and inaccurate prediction of biomass.

By means of simulation experiments it was proved that inaccurate estimation of variables of corn growth and development was caused by weather anomalies in 1997.

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4. New and latest scientifical results

- Soil water content of the upper 60 cm layer in spring and before sowing can be quite accurately simulated with the help of Ceres-Maize simulation model v. 3.5. However, the model underestimates measured values in deeper soil layers and does not consider the effect of excess water soaking from other soil layers into the observed layer.
- It was established that mineral nitrogen supply of soil in fertilized plots is considerably affected by tillage treatments applied at different soil depths. In disk-tilled plots this value is lower with 30-50 % compared to data of plowed plots. On the basis of the model run nitrogen losses can be attributed to denitrification occured in the autumn and winter period.

- According to our results individual crop yield in years with much rainfall does not accurately decrease in spite of shallow disk tillage treatment. Standard deviation of individual crop yield is not considerably influenced by any treatments. Neither tillage treatments nor the rate of fertilization and different plant densities causes consistently less or more heterogeneity in maize stand.
- On the grounds of lower and uneven plant densities measured in disk-tilled plots there is a considerable difference between the quality of the seedbed and the condition of the soil surface in both tillage treatments, consequently plant density at harvesting is basically affected by tillage treatments.
- Genetic coefficients of maize hybrids applied in the long-term tillage experiment were determined to run Ceres-Maize simulation model v. 3.5. By means of these parameters growing degree days from seedling emergence to the end of the juvenile phase (P1) and from silking to physiological maturity (P5), photoperiod sensitivity coefficient (P2), potential kernel number (G2) and potential kernel growth rate (G3) can be given.
- During the model validation and simulation experiments it was proved that the model predicted accurately phenological parameters, grain yield and biomass of maize and their seasonal dynamics if there were optimum soil and weather conditions for sowing and maize growth and development.
- The model is suitable for describing the effects of tillage treatments to a certain degree, because it is not sensitive enough to the effects of these treatments. It can only simulate their effects indirectly with the help of the input parameters such as bulk and plant density and values of nutrient and water supply of soil.
- According to our results Ceres-Maize model often over- and underestimates grain yield components, consequently further improvement is essentially required in this respect.

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