1. INTRODUCTION

The atmosphere-soil-plant system is very complex. The purpose of the crop models is to describe the processes of this system with mathematical tools and simulate them with the help of computers. Crop models use functions, differential equations and algorithms (procedures) for describing the processes of the system. For instance, one group of the procedures describes the development and the growth of plants, while another group calculates the water balance, etc. The model components that describe the main processes of the system are called sub-models or modules. The development of computer science enabled the scientists only in the 1970's to create the first crop model software applying the accumulated scientific knowledge. Since the water is the main driving force of the processes of the system the water balance module is one of the most important sub-models in crop models. Considering this the goals of my dissertation are the following:

1. Reviewing the history of the water balance sub-models.
2. Comparing the effectiveness of different kinds of water balance modules using measured data.
3. Reviewing some of the special problems of water movement modeling such as:
    a) Providing the required input data
    b) Bi- and multimodal soils
    c) Histeresys of the soil retention curve
    d) Bypass flow
4. Reviewing the solutions for overcoming the difficulties on the areas mentioned above.
5. Developing a crop model (software – 4M) that is suitable for educational and scientific purposes and applies the results of the work of several Hungarian and foreign scientists who are working on the field of soil science, meteorology and plant physiology.

6. Carry out sensitivity analyses for the water balance related parameters and modules of 4M.

7. Link 4M with different databases so that it could be used more widely.

2. Material and Method

2.1. The 4M

Last year a new workshop (4M) started to work within the Soil Science Society. The goal of this workshop is to create a crop model (4M) developed by Hungarian scientists. We chose the CERES model as a starting point, and continuously develop this model/software having two main goals:

1. Our goal is to create a model that enables the user to choose from different modules, which describe the same element of the system, depending on his aims and input data.
2. Our goal is to develop and incorporate data estimators that enable 4M to estimate input data, which are difficult to determine.

Since I am interested in the water movement in soils I started to develop 4M in this direction.

2.2. Comparing different kinds of water balance modules

In crop models the purpose of the water balance modules is to accurately describe the changes in the water distribution of the soil profile in space and time. All of these modules require the knowledge of the physical properties of the soil and the initial conditions of the system. They can be divided into 3 groups:

I. Simple water balance modules
II. Capacitive modules (tipping buckets)
III. Conductive modules (using the Richards' equation)

While 4M inherited a capacitive module from CERES, I incorporated a new conductive module into 4M.

2.2.1. Comparing the water balance modules with the help of 4M

The crop models usually include only one type of water balance module. It is very difficult to use different crop models for comparing their water balance modules because the models differ in many ways other than their water balance modules. Using 4M it is possible to carry out model runs where the only difference is the used water balance module. I verified the calculations of all of the water balance modules of 4M using measured data in the input files. I found that all three modules work realistically, so there is no programming error in them.

I investigated and compared the accuracy of each water balance module by comparing their results to water content data of field measurements. I used the average, absolute error between the measured and predicted water contents on the days when the measurements took place as a criterion.

2.2.2. Existing input data

In 1993 all the necessary input data (pF data, bulk density etc.) of the conductive module were determined for 4 spots of a site near Herceghalom. Between 05-18-1993 and 07-08-1993, and between 06-01-1994 and 10-03-1994 the water content of every 10 cm thick layer of the profile from 0 to 140 cm depth was measured with a capacitive probe every 10th day. All the required weather data were available for these time periods. I chose two spots for comparison. Winter wheat was sown on spot no. 1. while maize was sown on spot no. 4.

I used the pF0 data as a maximum water content and the pF4,2 data as a wilting point in the input data file of the capacitive module.

2.2.3. Input data determined by me

On spot no. 1. and 4. I determined the field capacity and the drain constant values of the layers of the soil profiles with a simple flood-experiment. After the water infiltrated we covered the profiles to prevent evaporation. Having waited several days till the water content of each layer stopped changing (it was monitored by using a capacitive probe), we took samples from every 10 cm from both of the profiles down to 150 cm and measured the water contents with gravimetric method. The field capacities were obtained by multiplying these water contents with the bulk densities of the layers.

Due to the installation procedure of the water content measurement the plants were missing right on the measurement spot. Because of this I assumed the presence of active roots only 30 cm depth and below. Since the water measurements were loaded with big errors at the soil surface I used only the 15-30, 30-50, 50-70 cm depths (for profile 1) and 20-50, 50-70 cm depths (for profile 4) in the comparison.

Having determined all the input data for the water balance modules, I carried out two model runs for the two profiles. The model runs differed only in the used water balance modules.

2.3. Sensitivity analyses

The crop models are differently sensitive for their components (their structure if it is a module or their value if it is a parameter). There are parameters whose value hardly influences the model results, while there are ones whose value-changes result in a big difference in the model calculations. Since the crop models are very complicated systems their sensitivity analysis is complicated as well. The model shows different sensitivity for their components in different weather circumstances. In rainy years the model is less sensitive. In this work all the sensitivity analyses were carried out with the help of a 20 year long weather database. I made 20 model runs with every model adjustment (parameter setting) according to the number of the years in the weather database. I defined the influence of input change on the output (ΔO) as it follows:

First, I calculated the absolute difference between the output obtained using the original input (o_i) and the output obtained with the altered input (o'_i) for every year. Then I divided these differences with the corresponding output obtained using the original input, and I calculated the average of these ratios for the 20 years [1].

[1] $$\Delta O = \frac{\sum_{i=1}^{20} \frac{|o_i - o'_i|}{o_i}}{20} \cdot 100$$

The model runs started on 1st of March in every year. I supposed that the initial available water contents of the investigated soil profiles were 150 mm. The plant used in the model runs was maize. I investigated the sensitivity of the models taking their most important outputs, such as: the date of flowering, the maximum value of LAI, as well as the yield and biomass into account.

The main purpose of the sensitivity analyses is to set directions for model improvements, including, in my opinion, the problem of obtaining quality input data for crop models. The parameters whose values the model is sensitive to should be measured and determined more precisely. Therefore, the modules the model is sensitive to ought to be improved first.

2.3.1. Sensitivity to the type of the retention curve

The user can select from two types of retention curves in the present version of 4M (*Brooks* and *Corey*, 1964; *van Genuchten*, 1980). I investigated the change in the output depending on which function was selected for the model run. I used two soil profiles having different water economy: chernozem (Pusztaszabolcs) and brown forest soil (Nyírlugos). First, I fitted a Brooks-Corey type of retention curve onto the measured pF data (*Rajkai* et al., 1981, *Várallyay*, 1987) and gave its resulted parameters as an input then I repeated this process with the van Genuchten curve. The K_S parameter was estimated by the *Campbell* (1985) method using the particle size distribution and bulk density data.

2.3.2. Sensitivity to the parameters of the retention curve

Next, I investigated how sensitive the model is to the changes of the parameters of the van Genuchten type of retention curve. I used the previously mentioned soils (chernozem, brown forest soil) for this analysis. First I used the Θ_S, Θ_r, α and n fitted parameters and the K_S estimated parameter as an input for the model runs then I changed these parameters (only one parameter of one horizon in every case) by ± 1 %; ± 2 %; ± 5 %; ± 10 % and monitored the changes of the output.

2.3.3. Sensitivity to taking the hysteresis into account

I incorporated a module for describing hysteresis (*Kool* and *Parker*, 1987) into 4M. The procedure uses the van Genuchten type of retention curve. Using this method all the scanning curves can be described knowing the main drying and wetting curves. I investigated the changes in the output that were caused by taking the hysteresis into account.

2.3.4. Sensitivity to taking the bypass flow into account

I incorporated a module into 4M that describes the preferential flow in swelling-shrinking soils. The module requires 3 additional input data:

1. Swelling curve for each layer in the profile.
2. Sum of the crack lengths on a unit area of the profile surface.
3. Maximum depth of the cracks.

I will not go into details about the procedure here. I used Tóth Tibor's soil data (Nyírőlapos) for testing the module (*Tóth* and *Jozefaciuk*, 2002). I created soil input files for two profiles and investigated the changes in the output that were caused by taking the preferential flow into account.

2.3.5. Sensitivity to taking the bimodality into account

4M is able to describe the water balance of soils with bimodal porosity and is able to fit the bimodal van Genuchten function onto the pF data. First, a profile from the database of RISSAC (*Rajkai* et al., 1981, *Várallyay*, 1987) (Mezőtúr: chernozem) having horizons (A, B1, BC) with bimodal porosity has been selected. Then an input file was created where the parameters of the unimodal van Genuchten functions were given as an input, then I created another one where I gave the parameters of the bimodal function as an input to the horizons that appeared to be bimodal. Two versions have been created of the later input file. In the first version I gave the same values both to the hydraulic conductivity of the soil matrix and to the macropores. In the second version I supposed that the macropores have a hydraulic conductivity one order of magnitude bigger.

Next, the difference between the output obtained by using unimodal retention curves only and the output obtained by using both uni- and bimodal functions was investigated.

2.3.6. Sensitivity to the way of calculating the potential evaporation

The user is able to select from three procedures for calculating the potential evaporation.

1. FAO-Penman (*Doorenbos* and *Pruitt*, 1977)
2. Priestley-Taylor (1972)
3. Szász (1973)

The database that was used (Pestlőrinc, 1968-87) contains all of the required input data for these procedures. 20 model runs were carried out (for every year) with each module and the differences were investigated in the corresponding output. I was especially interested in whether the procedure developed by Szász is sensitive to its wind speed or relative humidity input data or if they can be substituted with some kind of long term averages and can be neglected. Using the 20 year-long database the monthly averages of the wind speed and the relative humidity were calculated. I investigated how much the output would be altered if the monthly averages were used instead of the measured daily values.

2.4. Predictions of pedo-transfer functions as model inputs

For the majority of the conductive water balance modules the parameters Θ_S, Θ_r, α, n and K_S of the retention curve, as well as the conductivity function are the required input data for every horizon. If the pF data is available (the optimum case) the Θ_S, Θ_r, α and n parameters can be obtained by curve fitting. The hydraulic conductivity can be obtained by simple measurement. If the pF data are missing these parameters can be estimated by pedo-transfer functions using the bulk density, organic matter and particle size distribution data of the soil. The database of RISSAC (*Rajkai* et al. 1981; *Várallyay* 1987) contains data on 244 (non-silty: salt content < 0,1%) soil samples from 44 profiles (table 1.) of 34 sites: bulk density (TT), organic matter content (SZA), particle size distribution (H – sand; I – silt; A – clay) and pF data.

Soil type	db
Meadow soil	11
Meadow chernozem	12
Chernozem	16
Other	5

table 1.: **Profiles in the database of RISSAC**

This database has not been used for establishing pedo-transfer functions for predicting the parameters of the van Genuchten type of retention curve. *Wösten* and his colleagues (1999) have established the above mentioned pedo-transfer functions using the data of more than 5000 European soils (none of them from Hungary). Using the database of RISSAC I compared the predictions of Wösten's pedo-transfer functions to mine's. I investigated the possibility of substituting the measured parameters with predicted ones in the 4M crop model.

2.4.1. Establishing the pedo-transfer (PTF) functions

First, the soils in the database of RISSAC were divided into four groups considering their particle size distribution (figure 1.). Then, the van Genuchten type of function was fitted onto the pF data of each soil. Next, the obtained Θ_S, Θ_r, α and n parameters were correlated with H, I, A, TT, SZA data of the soils of each group using linear regression equations.

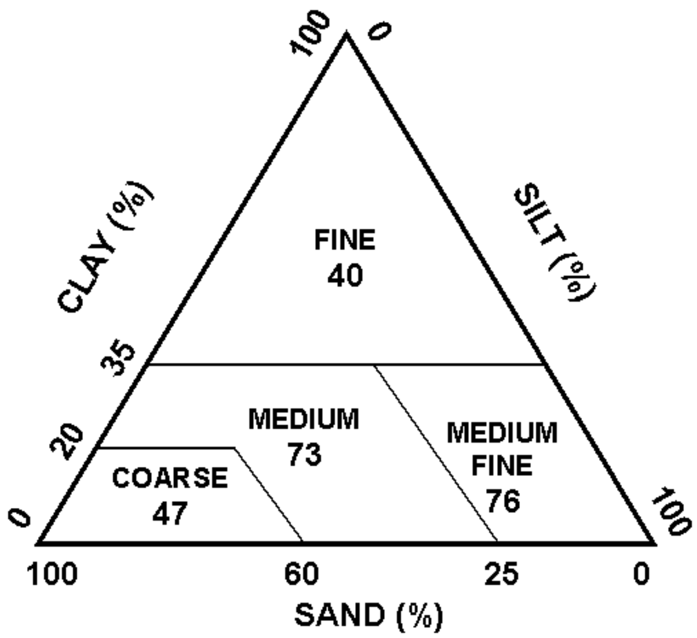

figure 1.: **244 non-salty soils of the database of RISSAC. 47 coarse samples etc.**

2.4.2. Comparing the pedo-transfer functions

I investigated the differences between the fitted retention curves and the measured water contents at pF = 0; 0,4; 1; 1,5; 2; 2,3; 2,7; 3,4; 4,2; 6,2 at all of the 244 soils of the database. The maximum of these differences (both downward and upward) were considered as limits of acceptability at suctions listed above. If the water content predictions of a retention curve whose parameters obtained by pedotransfer functions are between these limits the prediction is said to be acceptable at that particular suction. I investigated the 244 retention curves obtained by Wösten's pedotransfer functions and the curves obtained by my PTFs, to see whether their predictions were acceptable or not at the suctions listed above. Then I repeated this investigation on an independent database with the data of 10 soils (*Rajkai* et al. 1981; *Várallyay* 1987).

2.4.3. Estimations of PTFs as model input

Since there were no measured data on the hydraulic conductivity, the K_S parameters of the 244 soils were estimated using the *Campbell*'s (1985) method. 4 soil input files have been created for each of the 44 profiles in the 4M crop model:

1. The parameters have been determined by curve fitting for each of the horizons. (This the optimum case.)
2. The parameters have been estimated by my PTFs for horizon C. For the remaining part of the profile fitted parameters were used.
3. The parameters were estimated by my PTFs for horizons B and C. The parameters of horizon A were fitted ones.
4. Estimated parameters were given for the whole profile.

I used a 20 year long weather dataset (Pestlőrinc, 1968-87) for investigating the differences in the output (date of flowering, biomass, yield) depending on which input files were used during the model run. Next, I carried out 20 model runs with every type of input data for every profile and investigated the changes in the output using the 2-4 input files compared to results obtained by using the 1st input file. Every run had the very same initial conditions. For the 44 profiles 880 model runs were carried out for every type of input file (table 2.).

Soil type	Runs
Meadow soil	220
Meadow chernozem	240
Chernozem	320
Other	100
Total	880

table 2.: **Number of model runs with every type of soil input file.**

During field measurements 5-10 % differences were observed between the replicates of the yield, biomass etc. samples (*Huzsvai*, 2000). According to the developer of one of the most famous crop models the model results are acceptable if they do not differ from the observed values by more than 10% (*Ritchie*, 2000). Therefore, I have considered the estimations of the PTFs to be acceptable if their estimated parameters did not cause more than 10% change in the model output compared to the runs where fitted parameters (input file 1.) were used. I counted the acceptable runs (the acceptable PTF predictions) out of the runs carried out using the 2-4. type of input files for every soil type (table 2.)

2.5. Predicting the soil parameters using the Shao-Horton method

I investigated the accuracy of a recently developed method (*Shao* and *Horton*, 1998) for determining the parameters of the van Genuchten type of retention curve. The method is based on a horizontal infiltration experiment. In the study I used sandy (Nyíregyháza) and a loamy (Látókép) soil taken from the upper part of the profile (0-30 cm depth). The pF curves of the disturbed soils were determined (bulk density: 1,4 (sand) 1,3 (loam)) as well as their particle size distribution and organic matter. I calculated the parameters of the van Genuchten function of the two soils using my pedo-transfer functions and the method described below.

I determined the parameters of the two soils in two replicates with the Shao-Horton method. Since the method uses a very different way for determining these parameters (compared to the usual pF measurements) it is possible that its results will be very different from the parameters determined by the usual method.

During the pF measurements the main drying curve is determined while the Shao-Horton method uses a wetting process. The α parameter of the main wetting curve is always bigger than that of the main drying curve. I investigated whether the retention curve determined by using the Shao-Horton method is closer to the main wetting curve or to the main drying curve. I compared the estimations of the Shao-Horton method, and my pedotransfer functions.

2.5.1. Determining the main wetting curve

I filled 80 cm (for the sand) and 110 cm (for the silt) high columns with dry soils and put them into a flat vessel filled with water. Evaporation was prevented both from the vessel and from the soil surface. The vessels were refilled with water every day to the point where the soils did not suck more water. Then the columns were cut into 3 cm thick parts and the water content of the slices was measured. The main wetting curve was obtained by plotting the water contents against the distance from the bottom of the column.

3. RESULTS AND EVALUATION

3.1. Comparing different water balance modules using 4M

Knowing the detailed results of the model runs the following conclusions can be made:

1. Apart from some exceptions, both modules were able to describe the water balance of the two profiles within the measurement error limit.

2. The effectiveness of the two modules for describing the water balance of the two profiles was the same.

3. Cases with big differences between the measured and calculated water contents:

- Profile 1, depth 15-30 cm, 1994
- Profile 4, depth 20-50 cm, 1994
- Profile 4, depth 50-70 cm, 1994

3.1.1. Possible causes of the errors

1. It is very probable that the errors in profile 1 were caused by the surface runoff. The differences between the measured and calculated water contents can be decreased by changing the value of the runoff parameter (70 $\rightarrow$ 80) but cannot be completely eliminated. The water content measurements on the 202nd day (1994) show a rather strange phenomenon. Even though there was 29,1 mm of rainfall during the preceding three days, there is no sign for that in the 0-30 cm depth. The measured water contents on day number 202 (each of the 0-10, 10-20, 20-30 cm depths) show less water than the measurements on day 192. There was 5,3 mm of rain on day 192 however there was no rain for 10 days prior to that date. Still, the measurements show more water in the 0-30 cm depth on the 192nd day than on the 202nd day.

2. In 1994 there were four water content measurements (out of 12) that were taken on a rainy day. On the 181st day (06.30.) there were 11,6 mm of rain. Big differences were found between the measured and calculated values for that day (profile 4, depth 20-50 cm). It is possible that some of the precipitation infiltrated into the soil along the walls of the tubes installed into the soil for the measurements (artificial preferential flow).

3. In profile 4 (depth 50-70 cm, 1994 a continuous decrease of the water content can be observed from day 160 according to both of the measurements and the model calculations. This is an evidence for the presence of active roots. According to the measurements the water content reached some kind of a constant value at about 0,15 $cm^3 * cm^{-3}$ and around 0,18 $cm^3 * cm^{-3}$ according to the modules. I believe that this an evidence that the used presumption (wilting point equals to the water content at pF4,2) is questionable.

This study shows how complicated the system is which we are trying to describe with models. The most important statement that we can conclude is that, even though the capacitive module requires more easily determinable inputs and works faster than the conductive module, they gave very similar results in describing the water movement of the investigated soils. However, it is imperative to mention that these results are valid only if the water table does not affect the water balance of the root zone.

3.2. Sensitivity analyses

3.2.1. Sensitivity to the type of retention curve

The runs with the Brooks-Corey retention curve constantly gave higher yields. It is because this retention curve almost always gives higher water contents in the middle pF range (pF = 1,5 – pF = 2,7) than the van Genuchten function. There are considerable differences between the model outputs depending on which retention curve was used. In crop models I suggest using the van Genuchten function since it fits better to the measured pF data and therefore gives a better description of the retention curve.

3.2.2. Sensitivity to the parameters of the retention curve

Knowing the results of the runs the following statements can be made:

1. The model is more sensitive to the parameters of the horizons that are closer to the soil surface.

2. The model is more sensitive to the parameters of the horizons that give bigger parts of the profile. At the chernozem horizon A gave 24,4%, horizon B 25,6%, while horizon C gave 50% of the profile. These were 13,9%; 13,9% and 72,2% for the brown forest soil. Because of this the model was more sensitive to the parameters of horizon C of the forest soil than the chernozem.

3. Bigger changes in the parameters cause bigger changes in the output.

4. The parameters can be lined up in the following sensitivity order. The first is the parameter which the model is the least sensitive to: Θ_r, K_S, α, Θ_S, n.

5. The model is not sensitive to the K_S parameter. There can be one order of magnitude differences between the hydraulic conductivities of the replicates of the very same soil. Such changes of the K_S parameter caused 1-10% changes in the outputs with the chernozem and 5-20% changes with the brown forest soil.

Knowing the results above the following conclusions can be drawn:

1. In crop models it is very important to determine the parameters of horizon A precisely. In the cases where horizon A is thin the parameters of the deeper horizons should also be determined precisely.

2. The values of the parameters α and n (usually) are determined by the measured water content values: between pF = 0,4 and pF = 2,0 (for sandy soils), between pF = 1,5 and pF = 3,4 (for loamy soils), and between pF = 2,3 and pF = 4,2 (for clay soils). Because of this it is essential to carry out precise measurements in the corresponding pF ranges and/or increase the number of the measured pF points.

3. Considering the bimodal soils there can be huge differences between the Θ_S, α and n parameters depending on whether the unimodal or bimodal function was fitted on the pF points. There can be one order of magnitude difference between the α parameter of the unimodal and the bimodal functions. Such changes of the parameter α caused 10-20% differences in the output. Since the model is most sensitive to the parameters Θ_S and n, and the α of the bimodal function can be so different it is indispensable to use bimodal retention curves for bimodal soils in modeling their water balance.

3.2.3. Sensitivity to taking the hysteresis into account

Taking the hysteresis into account caused negligible changes in the outputs for the chernozem but caused significant changes for the brown forest soil. Further investigations should be made to establish whether this is a realistic result or not. As a first step the hysteresis module should be verified through experiments. The tool (4M) is ready. Based on this sensitivity analysis there is no need to take the hysteresis into account in crop models in case of soils having non-marginal water economy.

3.2.4. Sensitivity to taking the preferential flow into account

Checking the outputs of the runs it was turned out that although the crack were there in case of the profile 006 but never came a rain that's flux were bigger that the actual conductivity of the soil surface. It is not surprising because the surface conductivity of this profile was very high. Because of this there was no surface runoff no water went into the cracks. However the surface conductivity of the profile 249 was much lower surface runoff (and preferential flow) occurred only during very heavy showers and caused differences in the outputs. The reason for this is that I have only daily precipitation data without any information on its distribution during the day. In cases like this all the simulation models suppose the even distribution of the rain during the day. This results relatively low flux that causes only small surface runoff and preferential flow. I carried out model runs where I supposed that during the summer time all of the rainfall events that brought more than 25 mm precipitation lasted for only 20 minutes. I investigated how the water balance (profile 249) was changed because of this. The preferential flow module works realistically. The main conclusion I drew down is that modeling preferential flow definitely requires detailed rainfall data, measured more frequently that one day.

3.2.5. Sensitivity when taking the bimodality into account

Considering the result of the runs it is obvious that the difference was caused mainly by the changes of the shape (parameters) of the retention curve (using a bimodal function instead of a unimodal one). This change caused fairly big changes in the outputs, in fact the difference was bigger than the one caused by hysteresis. Since the description of the retention curve becomes more accurate using bimodal functions, the calculations of the model should be precise as well. Improving the model with this feature is necessary and meanwhile fairly simple.

3.2.6. Sensitivity for the method of calculating potential evapotranspiration

The model gave fairly different results depending on which potential evapotranspiration module was used. This means that the user should choose between the procedures that are available depending on the existing input data. If all the required input data is available I suggest using the procedure developed by Szász since it is an empirical method developed especially for Hungarian circumstances. If the relative humidity data is missing the FAO-Penman is the second best algorithm because its firm theoretical foundation. In case the wind speed data is not available the user can still use the Priestly-Taylor method.

In the Szász method only the wind speed data can be substituted by monthly averages. The model definitely requires the daily measured relative humidity values for proper calculations.

3.3. Comparing the estimates of pedo-transfer functions

I have pointed out that my method gave better water content estimates in the middle pF range (pF = 1,0 – pF = 3,4) than Wösten's method. For small and big suctions the two procedures gave identical results (table 3.).

	Acceptable predictions (%)	
pF	Fodor	Wösten
0,0	96,3	98,3
0,4	92,1	97,9
1,0	92,9	87,1
1,5	90,0	68,8
2,0	80,4	62,1
2,3	89,2	66,7
2,7	85,8	67,9
3,4	89,6	85,0
4,2	80,4	78,8
6,2	96,3	91,7

table 3.: **Acceptable water content estimates of the retention curves determined by Wösten's and Fodor's PTFs (out of 244 soils).**

This statistical analysis does not tell us how effectively can the estimations of my pedo-transfer functions substitute the required parameters of the conductive module in crop models. However, this comparison highlights one of the weak points of the pedo-transfer functions that is paradoxically the big potential of this method.

The pedo-transfer functions usually give good estimations for soils to which we have had similar ones in the base dataset that was used for developing the PTFs. Although Wösten (1999) used the data of more than 5.000 European soils (20 times more than I used but non of them were from Hungary) in comparison my pedo-transfer functions gave better estimations because they were calibrated on a Hungarian database. Based on this it is possible that if we could extend the database of RISSAC so that it would be representative enough for the Hungarian soils we could develop even better pedo-transfer functions.

3.3.1. Estimations of pedo-transfer functions as soil input data

I compared the results of the model runs having soil inputs obtained by curve fitting (onto the measured pF data) to the ones having inputs obtained by using pedo-transfer functions. This comparison has been carried out for all 44 soil profiles of the RISSAC database.

Knowing the results I concluded the following statements:

1. The calculated yield values were most sensitive to the substitution of the input data with estimated ones. The maximum of the LAI was the least sensitive to this change. The maximum of the LAI is influenced by the water balance only before flowering. It seems that the predicted input data cause less difference during shorter periods of time.

2. In case of chernozem soils the predictions of the pedo-transfer functions are 10-20% more reliable than in case of other soil types. In the database the chernozem gave the majority of the soils (table 1.). This fact proves my point that the effectiveness/usefulness of the pedo-transfer functions could be increased by extending the database of RISSAC.

3. In rainy years the pedo-transfer functions gave 5-15% more acceptable predictions. In these years usually there is enough water in the soil, so the importance of the way of the water balance (and the way of modeling the water balance) decreases. In rainy years it is safer to use the predictions of pedo-transfer functions in crop models.

4. One can get 10% more acceptable model runs if measured-fitted parameters are given to the horizon A and predicted ones to the horizon B and C instead of giving estimated parameters to all of the horizons of the profile. Usually it is enough to use pF measurement and curve fitting for determining the soil input parameters only of the horizon A and the parameters for the rest of the profile can be determined by pedo-transfer functions.

5. If the only purpose of using the crop model is to predict the biomass then the pedo-transfer functions can give acceptable estimates (substitutions) for the soil inputs in more

than 85% of the cases (in rainy years more than 90%) in the case of chernozem soils. In the case of other soil types this ratio is only 70% (80 % in rainy years).

3.4. Predicting the soil parameters using the Shao-Horton method

Bellow is a summary of the results of this method' analysis:

1. The h(Θ) functions (drying curve) obtained by pedo-transfer functions gave a better description of the retention curves than the ones that were derived by using the Shao-Horton method. The difference between the two methods (PTF and Shao-Horton method) is really emphatic within the range of pF = 1,0 – pF = 3,4 which is a very common phenomenon in field conditions. Considering these the PTFs are better tools for estimating the parameters of the retention curve.

2. The retention curve obtained by the Shao-Horton method is very similar to the main wetting curve in case of the sandy soil. The estimated retention curve shows bigger hysteretic effect than the measured wetting curve. One possible explanation is the increase of the contact angle during flow events that does not occur during the measurement of the wetting curve. In case of the loamy soil the retention curve obtained by the Shao-Horton method is similar to the wetting curve only for bigger suctions.
3. Considering the result, in my opinion the Shao-Horton method is not precise enough for predicting the parameters of the retention curve. One further disadvantage of the method is that it can be carried out only for disturbed soils.

3.5. Linking 4M with the SOTER database

As a first step enabling 4M to be used on larger scales I linked the model with the SOTER (Soils and Terrain Digital Database) database through a user-friendly interface. The missing data (required input data for the model) in the database have been estimated with pedo-transfer functions using the available data in the dataset. The soil data of all the SOTER units can be loaded and used in model simulations by clicking on a digital map provided by 4M.

3.6. Main characteristics of 4M

As I was writing my dissertation, with continuous development I finished the 2.0 version of 4M. The software was tested at the University of Debrecen. Following is a brief summary of the main characteristics of the latest version of 4M.

The characteristics that CERES already had have been marked with **

The new modules whose procedures were developed by other scientists and which have been incorporated into 4M have been marked with *.

All the parts that have not been specially marked have been developed and programmed by me.

1. 4M has a user-friendly interface that communicates in Hungarian and English.
2. 4M includes solar radiation estimating procedures developed by *Szász** (1968) and *Fodor* (*Fodor* et al., 2000).
3. 4M includes three procedures for calculating the potential evapotranspiration: *FAO-Penman*** (1989), *Priestley-Taylor*** (1972), *Szász** (1973).
4. 4M is able to model maize, wheat and barley.**
5. 4M includes a capacitive** and conductive* (*van Dam* et al., 1997; *Simunek* et al., 1998) water balance module.
6. 4M includes a module for curve fitting: *van Genuchten*, *Brooks-Corey* and *Ahuja-Swartzendruber* type of retention curve*. 4M is able to fit a bimodal retention curve onto the pF data.
7. 4M is able to describe the water balance of bimodal soils.
8. 4M includes two pedo-transfer functions for calculating hydraulic conductivity: *Campbell** (1985) and *Wösten** (1999).
9. 4M includes three sets of pedo-transfer functions for calculating the retention curve *Rajkai** (1987), *Wösten** (1999) and *Fodor* (chapter 3.4.1.).
10. 4M includes two sets of pedo-transfer functions for calculating the saturated water content, field capacity and wilting point: *Ritchie** (1999) and *Rajkai** (1987)
11. 4M includes a module for describing hysteresis: *Kool* and *Parker** (1987)
12. 4M includes a module for describing preferential flow (chapter 3.3.4.).
13. 4M is able to describe the effect of irrigation, inorganic and organic fertilization.**

14. 4M is able to handle 100 year long runs (with crop rotation).
15. 4M includes a graphical tool that can present two output variables of five runs at the same time.

4. NEW SCINTIFIC RESULTS

1. Improving the CERES crop model I developed a user friendly software package (4M) that has several new characteristics compared to its predecessor. 4M is suitable for educational and scientific purposes and applies the results of the work of several Hungarian and foreign scientists who are working on the field of soil science, meteorology and plant physiology. 4M has been linked with the SOTER database.

2. During the sensitivity analises of 4M I pointed out that:

   a) It is crucial for the crop models to precisely determine the parameters of the A horizon. It is indispensable to use bimodal retention curves for soils showing bimodal characteristics.

   b) the effect of hyteresis on model output is negligible for soils having normal water economy.

   c) In order to take the effect of preferential flow into account in the water balance it is indispensable to know the distribution of the daily rainfall during the day.

3. Using the dataset of RISSAC (particle size distribution, bulk density, organic matter content and pF data of 244 non-salty soils) I developed pedo-transfer functions for predicting the parameters of the van Genuchten type of retention curve. Retention curves derived with my pedo-transfer functions gave acceptable water content estimations with 80-95 % certainty. If modeling the biomass is the only purpose, the estimations of pedo-transfer functions can substitute soil data inputs with more than 85 % reliability (with more than 90 % in rainy years) in chernozem soils.

4. The investigated Shao-Horton method was found to be inadequate for estimating the soil hydraulic parameters. The estimations of the pedo-transfer functions gave better results according to the comparison.

5. Even though the capacitive module requires more easily determinable inputs and works faster than the conductive module, still they give very similar results in describing the water movement of the investigated soils.

5. Publications

5.1 Scientific papers

1. **FODOR N.**, KOVÁCS G. J., KARUCZKA A. (2001) A CERES modell továbbfejlesztése I. A Richards egyenlet beépítése után, összehasonlítás az eredeti változattal. Agrokémia és Talajtan 50:35-46.

2. **FODOR N.**, KOVÁCS G. J. (2001) A CERES modell továbbfejlesztése II. A Richards egyenlet paramétereinek meghatározása mérések ill. pedotranszfer függvények segítségével. Agrokémia és Talajtan 50:47-61.

3. **FODOR N.**, GABRIELLA MÁTHÉNÉ-G., KLÁRA POKOVAI AND GÉZA J. KOVÁCS (2002) 4M - software package for modelling cropping systems. European J. of Agr. 00:000

4. MÁTHÉNÉ GÁSPÁR G., DOBOS A., **FODOR N.** (1999) A termőhely és az agrotechnika hatása kukoricahibridek szemtermésének víztartalom-dinamikájára. Növénytermelés 48: (4) 413-420.

5. KOVÁCS G.J. ÉS **FODOR N.** (2001) A biomassza termelés érzékenysége a sugárzási energia változékonyságára hazánkban. A légköri erőforrások hasznosításának meteorológiai alapjai 169-176. OMSZ, Budapest, 2001

5.2. Talks and posters on conferences

1. **FODOR N.**, KOVÁCS G.J., RITCHIE J.T. (2000) A New Solar Radiation Generator for Hungary. Poster. ASA-CSA-SSSA, Annual Meetings. November 5-9, 2000, Minneapolis, MN, Abstract pp. 23.

2. **FODOR N.,** G.J. KOVÁCS (2001) 4M: an educational model to simulate agricultural systems. Book of proceedings 225-226., 2nd International Symposium Modelling Cropping Systems, Florence, 16-18 July, 2001, Italy

3. KOVÁCS, G.J., RITCHIE, J.T., MÁTHÉNÉ ,G.G., NAGY,J., DOBOS, A., **FODOR, N.** (1999) Modelling the process of drying of maize kernels. Proceedings of the ESA International Symposium Modelling Cropping Systems, Lleida, 21-23 June, 1999, Spain, 95-96.

4. NAGY, J., HUZSVAI, L., MIKA, J.,DOBI, I., **FODOR, N.**, KOVÁCS G.J. (1999) A Method to Link General Circulation Model to Weather Generator and Crop Models for Long Term Decisions, MODSS'99 Conference, Brisbane, Australia 1-6 August, 1999.

5. KOVÁCS G.J., **FODOR N.** 2000. Application of Agronomic Modeling in Research, Education, and Practice. ASA-CSA-SSSA, Annual Meetings November 5-9, (2000) Minneapolis, MN, Abstract pp. 30.

6. KOVÁCS G.J., NÉMETH T., ZSIGRAI GY., MÁTHÉ-GÁSPÁR G., **FODOR N.**, POKOVAI K. (2000) CERES Applications in Research of Nitrogen in the Environment and Production. Poster. ASA-CSA-SSSA, Annual Meetings November 5-9, 2000, Minneapolis, MN, Abstract pp. 24.

7. TIBOR TÓTH, D. SUAREZ, **N. FODOR**, G. VÁRALLYAY, L. BLASKÓ, G. CRESCIMANNO AND G. SZENDREI (2001) Short and Long Term Changes in Soil Salinity in Hungary. Oral. International Union of Soil Science, Sub-commission A, Bouyoucos Conference on Sustained Management of Irrigated Land for Salinity and Toxic Element Control, Jun. 25-27, University of California, Center for Water Resources George E. Brown Jr. Salinity Laboratory, USDA-ARS