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SOIL STRUCTURE PARAMETERS IN MODELS OF CROP GROWTH AND YIELD PREDICTION. PHYSICAL SUBMODELS

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A b s t r a c t. The role of chosen soil structure parameters in models of crop growth and yield prediction has been analysed on the base of the review of the latest literature. It was stated that the most frequently appearing soil parameters in the chosen models are soil water retention, rooting system, unsaturated and saturated hydraulic conductivity, bulk density or porosity. Comparison of submodels of physical processes in soil-plant-atmosphere continuum in chosen yield production models (CTSPAC, WOFOST, EPIC, CERES-maize) has been presented.

K e y w o r d s: soil structure parameters, crop growth and yield prediction models, physical submodels.

INTRODUCTION

Soil characteristics and parameters play an important role in building the majority of crop production models, especially those which consider interactions between different processes in soil-plant-atmosphere continuum determining the actual crop growth and yield. There is a high diversity in the amount of soil data required for different crop simulation models.

The role of soil structure parameters in models of plant growth and yield was determined in the following stages:

- comparison and selection of the soil structure parameters,
- review of the crop yield models,
- evaluation of frequency of appearing of the soil structure parameters in crop yield models,
- physical submodels comparison.

COMPARISON AND SELECTION OF THE SOIL STRUCTURE PARAMETERS

In the frame of the first stage the whole range of parameters was analysed to choose the parameters which directly characterise the status of the soil. The selection was performed during the workshops of multilateral co-operation between scientific institutions of Austria, Hungary, Czech, Slovakia, and Poland, with the representatives of Germany, the Netherlands and Russia. It was decided that the following parameters should be included in this analysis:

Inherent soil properties
Particle size distribution
Particle density
Chemical parameters
pH (H_2O, KCl, $CaCl_2$)
Electrical conductivity
$CaCO_{3tot}$
Organic matter
CEC
Exchangeable cations
N, P, K, heavy metals
Specific surface
Mineralogical parameters
Clay mineralogy
Total mineralogy
'Free' Fe-, Al-, Mn- oxides
Structural state parameter
Bulk density and porosity

Standard bulk density
Bulk density of aggregates
Swelling and shrinking of soils
Soil water retention (pF)
Water, air and energy flow parameters
Solute, air and energy transport
Saturated hydraulic conductivity
Unsaturated hydraulic conductivity
Bypass flow
Air diffusion
Air permeability
Oxygen diffusion rate
Redox potential
Soil strength and stability
Compaction test
Penetration resistance
Soil morphology
Soil thin sections
Morphometric characterization of thin sections
Submicroscopy
Macropore continuity
Soil biology
Enzymatic activity
Respiration rate
Meso- and macrofauna
Rooting system.

REVIEW OF THE CROP YIELD MODELS

In the frame of the second stage of the investigations the literature analysis was performed:

- from California University Library (MELVYL SYSTEM) the list of publications from the last four years was collected which includes the following thematic groups:
  * crop yield models (14 items)
  * crop models (54 items)
  * crop production (223 items)
  * soil degradation (153 items)
  * soil protection (27 items)
  * limiting factors (133 items)
  * soil quality (99 items)
  * solid phase (14 items)
  * soil structure models (18 items)
  * testing soil parameters (1 item)
  * soil productivity models (12 items)
  * yield models (206 items).
- from the Proceeding of the XV Congress of ISSS in Acapulco 100 publications were chosen referring to yield modelling.
- additional 146 reference publications were collected from different libraries.

The total number of considered publications was 1200. Some of these publications did not concern physical-mathematical models describing experiments or procedures of validation. There were several publications included in two or more groups of items. Finally the number of publications with models was 251.

In 203 publications presented models did not include soil structure parameters, estimating crop production on the basis of physiological, climatic or other phenomena. In 176 publications presented models did not contain above mentioned soil structure parameters and the yield was determined mainly on the base of physiological and climatological phenomena. The number of publications including models with soil structure parameters was 75. The number of models contained in these publications was 60.

The choosen models were divided into three types:

- correlation models (Table 1) - 10 models [1,5,6,17,18,35,54,63,67,71,72,76],
- models based on statistical analysis with the use of physical equations (Table 2) - 20 models [2-4,7,13,14,20,27,28,30,34,39,44,47, 55,57,66,77,81,83],
- physical-mathematical models based on consti- tutional equations with the elements of statistical-empirical coefficients (Table 3) - 30 models [8-12,15,16,21-26,29, 31-33,36-38,40-43,45,46,48-53,56,58-62,64,65,68-70,73-75,78-80, 82].

FREQUENCY OF APPEARING OF SOIL STRUCTURE PARAMETERS IN CROP YIELD MODELS

As follows from the Tables 1-3 (column 3), the soil structure parameters appear in these models with different frequencies. It was assumed that the frequency of a parameter's appearing in the models can be used for the estimating of its importance in the modelled process of the crop growth and yield. The result

Table 1. Correlation models

Models	Processes treated	Soil parameters included
*** (a submodel for SORGF) 1989 Rogers D., Elliot R.; Oklahoma State University, USA *sorghum*	Cost loss risk analysis, crop growth rainfall forecast	Soil water retention (pF)
*** 1990; Wallender W.W., Ardila S., Rayej M. University of California, USA *cotton-lint and others*	Infiltration, drainage, furrow irrigation	Soil water retention (pF), rooting system, electrical conductivity
*** 1990; Swan J.B., Staricka J.A., Shaffer M.J. *et al.* University of Minnesota, Colorado State Univ., University of Wisconsin *corn*	Soil water flow, evapotranspiration, water stress, management	Soil water retention (pF), rooting system, unsaturated hydraulic conductivity, saturated hydraulic conductivity
SSLRC 1991; Thomasson A.J., Jones R.J.A. SSLRC Silsoe, Bedford, UK *common, crops*	Site hydrology, drainage, evapotranspiration, workability, trafficability	Soil water retention (pF), rooting system, bulk density and porosity, saturated hydraulic conductivity, particle size distribution, organic matter, free Fe, Al, Mn oxides, depth of soil profile, water table depth
*** 1991; Corsini P.C. State of Sao Paulo University, Brazil *any crop*	Unsaturated hydraulic conductivity, saturated hydraulic conductivity, organic matter, soil structural stability	Soil degradation, economics, political interference in production
*** 1992; Abbaspour K.C., Hall J.W., Moon D.E. CLBRR, RSAC, Vancouver, Canada *any crop*	Evapotranspiration, crop phenology, soil water balance	Soil water retention (pF), water storage capacity
*** 1992; Craft E.M., Cruse R.M., Miller G.A. Iowa State University, USA *corn*	Soil erosion, root distribution, nutrient uptake, water uptake	Soil water retention (pF), rooting system, bulk density and porosity, particle size distribution, pH (H_2O, NCl, $CaCl_2$), solute, air and energy transport
*** 1992; Oropeza-Mota J.L., Martinez E., Berbez J. *bean, corn*	Soil erosion, hydraulic properties	Soil water retention (pF), rooting system, bulk density and porosity, pH (H_2O, NCl, $CaCl_2$)
*** DANSTRESS 1993; Jensen C., Svedsen H. *et al.* Denmark, Germany, *barley*	Atmospheric water flow, crop interception of water, photo-synthesis, soil water relations	Soil water retention (pF), rooting system, unsaturated, hydraulic conductivity, solute, air and energy transport
*** 1993; Shani U., Hanks R.J. Utah State University, USA *barley, corn and others*	Boron and inert salt concentration in the soil, water flow	Soil water retention (pF), rooting system, unsaturated hydraulic conductivity

Table 2. Models based on statistical analysis with the use of physical equations

Models	Processes treated	Soil parameters included
*** (SDI) 1971; Hiler E.A., Clarck R.N. University of Texas, USA; *any crop*	Transpiration rate, plant stress, crop susceptibility	Soil water potential
*** (submodel) 1972 Zur B., Bresler E. *any crop*	Irrigation regime, quality of irrigation water, soil water and salt balance	Soil water retention (pF), rooting system, unsaturated hydraulic conductivity, water table depth
*** 1983; Cassel D.K., Ratliff L.F., Ritchie J.T. USDA, ARS. SCS, Texas University *any crop*	Soil water status, physical and chemical processes in the soil	Soil water retention (pF), bulk density and porosity
TOMMOD, 1986 Wolf S., Rudick J., Marani A.,Rekah Y. Hebrew University of Jerusalem, Rehovot, Israel *tomato*	Soil aeration, plant growth	Soil water status
*** (submodel) 1988 Patwardhan A.S., Nieber J.L., Moore I.D. University of Minnesota, St. Paul, USA	Water infiltration, percolation, soil evaporation, oxygen and carbon dioxide transfer, gas diffusion	Water content, hydraulic conductivity, root water extraction function
*** 1989; Warrick A.W., Letey J.A. University of Arizona, Tucson, USA *any crop*	Root zone salinity, water consumption, irrigation	Soil water retention (pF), rooting system, bulk density and porosity, unsaturated hydraulic conductivity, saturated hydraulic conductivity, particle size distribution
TUNNEL 1989; Albright L.D., Wolfe D., Novak S. Cornell University, Ithaca, NY, USA *vegetables*	Soil insolation, thermal radiation exchange, ventilation	Soil thermal conductivity, soil surface emittance, soil surface absorbance, soil volumetric heat capacity
*** 1990; Massee T., USDA-ARS *winter wheat*	Erosion, water storage, yield	Soil water retention (pF), rooting system
*** 1991; Arvidsson J., Hakansson I. Swedish University of Agricultural Sciences *any crop*	Crop yield losses caused by machinery soil compaction iduced	Soil water retention (pF), particle size distribution, clay mineralogy
*** 1991; Brisson N., Perrier A. Institut National de la Recherche Agronomique, Avignon, France; *any crop*	Evapotranspiration	Soil water retention (pF), bulk density and porosity, soil type

*** 1991, Dinar A., Rhoades J.D., Nash P., Waggoner B.L., University of California, USA *wheat, sorghum*	Soil salinity, soil water relations, drainage	Soil water retention (pF), average salt concentration
*** 1991, Jefferies R.A., Heilbronn T.D. Scottish Crop Research Institute, Invergowrie Dundee DD25DA, UK *potato*	Canopy growth, light interception, biomass	Soil water retention (pF)
*** 1991, Amir J., Sinclair T.R. Gilat Experimental St., Israel spring wheat	Leaf growth, leaf gas, exchange, water balance	Soil water content, soil depth
*** 1992, Prendergast J.B. ISA, Victoria, Australia *any crop*	Salinity, irrigation	Water content
*** 1992, Santos J.R.A., Gomez A.A., Rosario T.L. Texas A. and M. University, USA Center of Agriculture, Lagune, Philippenes *tomato*	Nutrients, solar radiation, water and energy balance	Water content, infiltration rate, soil texture, percolation rate, saturation point, field capacity, wilting point
GLOBAL 1992, Majercak J., Novak V. Institute of Hydrology SAV Bratislava, Slovakia *any crop*	Water transport in soil	Depth of water table, unsaturated and saturated water conductivity, intensity uptake by roots
*** 1993, Gupta R., Abrol I.P. IA RI, New Delhi, India maize, sorghum, black gran, tuber and others	Soil compaction infiltration, tillage, soil quality	Bulk density and porosity, unsaturated hydraulic conductivity, saturated hydraulic conductivity, saturated hydraulic conductivity, organic matter, depth of soil profile, water table depth
*** 1993, Ghuman B.S., Singh C.B. Punjab Agricultural University *different rotations*	Atmospheric radiation, global radiation dry matter production	Soil water retention (pF), unsaturated hydraulic conductivity, saturated hydraulic conductivity, solute, air and energy transport, respiration rate
*** 1993, Lal R. DA, The Ohio State University, Columbus *any crops*	Soil stability and degradation	Soil water retention (pF), rooting system, electrical conductivity, depth of soil profile
*** 1993, Acs F. University of Novi Sad, Yugoslavia *winter wheat, sugar beet*	Radiation, heat and moisture, transfer	Soil heat capacity, soil thermal conductivity, soil moisture content, soil potential

Table 3. Physical-mathematical models based on constitutional equations with the elements of statistical-empirical coefficients

Models	Processes treated	Soil parameters included
CERES-WHEAT 1972, Ritchie R.T., Otter S. USDA/SEA (Texas) *wheat*	Phasic development, morphogenesis, growth, biomass accumulation and partitioning soil water balance, plant-soil nitrogen status	Soil water retention (pF), bulk density and porosity, particle size distribution, solute, air and energy transport
*** 1973, Nimah M.N., Hanks R.J. Utah State University, USA *any crops*	Water content profiles, evapotranspiration, water flow, root extraction	Soil water retention (pF), rooting system, unsaturated hydraulic conductivity, water table depth
*** 1974, Hanks R.J., Utah State University, USA *sorghum, corn and others*	Transpiration, evaporation, drainage, dry matter production	Soil water retention (pF), rooting system
GRAGRO 1975 Olszta W., IMUZ, Lublin *grass*	Evapotranspiration, water table movement, soil tension moisture dynamics, dry matter production of grass	Temperature of soil, pF curve, unsaturated hydraulic conductivity, root density, field capacity of soil
*** 1977, Childs S.W., Gilley J.R., Splinter W.E. University of Nebraska, Lincoln, USA *corn*	Root growth, evapotranspiration, soil water flow, crop growth, photosynthesis, respiration, dry matter production	Soil degradation, economics, political interference in production
SWATR, SWATRE, ONZAT, SWANY, CROP SWACROP 1978 *any crop*	Soil water balance, energy balance, plant growth, photosynthesis, evapotranspiration	Soil water retention (pF), unsaturated hydraulic conducti-vity, depth of soil profile
DRAINMOD, Skaggs R.W., *et al.* North Carolina State University, USA *any crop*	Runoff subsurface drain flow, water table depth fluctuations, drain outflows	Soil water retention (pF), rooting system, bulk density and porosity, saturated hydraulic conductivity, depth of soil profile
CREAMS (a submodel for CERES, EPIC) 1980-92 Krusel W.G., Silburn D.M., Freebairn D.M. *any crop*	Runoff, salinity, soil moisture, drainage	Soil water retention (pF), rooting system, bulk density and porosity, saturated hydraulic conductivity, depth of soil profile
UGWTPN 1981, Olszta W., IMUZ, Lublin *grass*	Water transport in unsaturated zone, water uptake by roots, evapotranspiration, plant growth	pF curves, hydraulic conductivity as a function of potential, soil porosity, water table depth
GLYCIM 1982, Acoock B., Reddy V.R., *et al.* USDA-ARS, Misisipi State Univ. and Univ. of Florida *soybean*	Photosynthesis, respiration, transpiration, growth, morphogenesis	Soil water retention (pF), unsaturated hydraulic conductivity, saturated hydraulic conductivity, solute, air and energy transport, respiration rate

EPIC 1983, Williams J.R., Jones C.A., Dyke P.T. USDA-ARS Texas University, *any crop*	Erosion, plant growth, runoff, percolation, evapotranspiration, drainage, irrigation	Soil water retention (pF), bulk density and porosity, particle size distribution, pH (H_2O, NCl, $CaCl_2$), solute, air and energy transport, depth of soil profile, albedo
*** 1985, Stewart D.W., Dwyer L.M. LRRI, Agrometeorology Section, Ottawa, Canada, *maize*	Plant growth, potential and actual transpiration	Soil water potential, soil water content, soil hydraulic conductivity, saturated soil content, soil texture
CERES-MAIZE 1986, Jones C.A., Ritchie R.T. USDA/SEA (Texas) and IFDC Alabama, *corn*	Phasic development, morphogenesis, growth, biomass accumulation and partitioning soil water balance, plant-soil nitrogen status	Soil water retention (pF), bulk density and porosity, particle size distribution, solute, air and energy transport
GOSSYM 1986, Baker D.N., Lombert J.R. USDA/SEA (Mississippi) and Clemson Univ., *cotton*	Photosynthesis, respiration, growth and morphogenesis	Soil water retention (pF), unsaturated hydraulic conductivity, saturated hydraulic conductivity, solute, air and energy transport, respiration rate
GLEAMS, GLEAMS-WT (a submodel) 1987 Rayes M.R., Bengtson R.L., *et al.*, Louisiana State University, USA, *soybean*	Runoff, evapotranspiration, soil movement seepage, peak flow, crop rotation, infiltration, percolation	Soil water retention (pF), rooting system, bulk density and porosity, saturated hydraulic conductivity
SIMCOY 1987 Place R.E., Brown O.M., Univ. Guelph, Ontario, Canada *corn*	Phenological phases, root growth, leaf area, soil moisture budget, evaporation, transpiration, yield	Soil type, K-coefficient, available soil moisture
WOFOST, 1988 Depen C.A. van, Rappoldte, Wolf J., Kenlen H. van Agricultural University, Wageningen, Holland *any crop*	Evapotranspiration, crop growth, soil water balance	Moisture content of root zone, depth of ground water table, percolation rate, rate of capillary rise, runoff, surface storage, soil evaporation rate, rooting depth, rate of net influx through the lower and upper root zone boundaries
*** 1990, Robinson J.M., Hubband K.G. Louisiana State Univ., University of Nebraska, USA *corn, wheat, sorghum, soybean*	Soil water status, evapotranspiration	Soil water retention (pF), rooting system, bulk density and porosity, unsaturated hydraulic conductivity, saturated hydraulic conductivity, particle size distribution
ARORA 1990, Edwards D.E., Ferguson J.A., Fryar E.O. University of Arkansas, Fayetteville, USA *any crop*	Reservoir and soil water balances, a quifer response to pumping, irrigation, actual and potential transpiration	Soil water retention (pF), unsaturated hydraulic conductivity, saturated hydraulic conductivity, water table depth, water storage capacity
Modification of SWACROP 1990 Ragab R., Beese F., Ehlers W. Institute of Hydrology, Oxfordshire, UK, *oat*	Water uptake, evapotranspiration, stomatal resistance, water storage in the soil profile	Soil water retention (pF), rooting system, unsaturated hydraulic conductivity, respiration rate
BIOMASS 1990, Murtrie R.E., Rook D.A., Kelliher F.M. CSIRO, Div. Forestry, Canberra-Australia, Rotorua-Nowa Zelandia *pinus radiata*	Water balance, canopy net annual photosynthesis, fertilizer impact, respiration, crop production	Water storage, soil water retention, plant available water

AQUA 1990 Radulovich R., University of Costa Rica, San Jose, Costa Rica *rice, beans, corn*	Water balance, potential evapotranspiration, crop growth	Available water, rooting depth
CTSPAC 1990, Lindstrom F.T., Boersma L., Yingjajaval S. Oregon State University, Corvallis, USA Kasetsart University, Thailand *any crop*	Water transport in soil and plant, energy balance at the air soil surface, transport and storage of chemicals in plants, transpiration	Water characteristics, soil thermal characteristics, characteristics of soil solid phase, soil and water chemical characteristics
*** 1991, Johnson K.B. Oregon State University, Corvallis, USA *potato*	Growth, plant diseases, insect pests, radiation, interception	Soil water retention (pF), unsaturated hydraulic conductivity, depth of soil profile
SOYGRO, PNUTGRO, BEANGRO 1992-93 Wilkerson G.G., Jones J.W. *et al.* University of Florida *soybean, peanut, beans*	Photosynthesis, respiration, growth senescence, phenology, infiltration, drainage, transpiration	Soil water retention (pF), rooting system, unsaturated hydraulic conductivity, saturated hydraulic conductivity, albedo
RICEMOD 1992, Rao N.H., Rees D.H. International Rice Research Institute L.A.R.I. New Delhi, India *rice*	Photosynthesis, respiration growth	Soil water retention (pF), rooting system, unsaturated hydraulic conductivity
SIMPOTATO 1992, Hodges T., Johnson S.L., Johnson B.S. Michigan State University *potato*	Photosynthesis, respiration, evapotranspiration, soil water balance, morphogenesis, plant growth	Soil water retention (pF), bulk density and porosity, unsaturated hydraulic conductivity, saturated hydraulic conductivity, organic matter, pH (H_2O, NCl, $CaCl_2$), depth of soil profile, albedo, soil type
PERFECT 1992, Littleboy M., *et al.* Queensland Department of Primary Industries, Brisbane, Australia *any crop*	Runoff, deep drainage, erosion, water balance, crop growth, residue and crop cover	Soil water retention (pF), bulk density and porosity, unsaturated hydraulic conductivity, saturated hydraulic conductivity
FORYLD 1994, Bootsma A., Boisvert J., Dumanski J. CLBRR Ottawa, Canada, FAO - sponsored *legumes grasses*	Phasic development, biomass, evapotranspiration, fertilizer application	Soil water retention (pF)
CORNWAY 1995, Majercak J., Novak V., Vidovic J. Institute of Hydrology SAV, Bratislava, Slovakia *maize*	Vertical water transport, water uptake by roots, dry matter production	Depth of water table

Table 4. Frequency of appearing of soil structure parameters in selected models

Soil parameters \ Model	Frequency of appearing (%)			
	Correlation models	Models based on statistical analysis with the use of physical equations	Physical-mathematical models based on constitutional equations with elements of statistical-empirical equations	All the models
Soil water retention	90	85	100	93
Rooting system	70	15	53	43
Unsaturated hydraulic conductivity	40	20	53	40
Saturated hydraulic conductivity	30	15	47	33
Bulk density or porosity	30	25	37	32
Solute, air and energy transport	20	15	23	20
Particle size distribution	20	10	17	15
Organic matter	20	10	10	12
pH (H_2O, KCl, $CaCl_2$)	2	5	7	8
Electrical conductivity	10	5	-	3
Respiration rate	-	-	7	3
CEC	-	5	3	3
$CaCO_3$	-	5	-	2
Clay mineralogy	-	5	-	2
Free Fe, Al, Mn, oxides	10	-	-	2

of this analysis is presented in Table 4 for each type of models separately and jointly. It is seen that the most frequently appearing parameters in the chosen models are:

- soil water retention,
- rooting system,
- unsaturated and saturated hydraulic conductivity,
- bulk density and porosity.

In Table 5 the result of review is presented

Table 5. Frequency of appearing of additional soil structure parameters in selected models

Additional soil parameters \ Model	Frequency of appearing (%)			
	Correlation models	Models based on statistical analysis with the use of physical equations	Physical-mathematical models based on constitutional equations with elements of statistical-empirical equations	All the models
Soil profile depth	10	15	20	17
Water table depth	10	10	17	13
Water storage capacity	10	10	10	10
Soil type	-	10	10	8
Albedo	-	-	13	7
Soil structural stability	10	5	3	5
Average salt concentration	-	5	-	2
Terrain slope	-	5	-	2

for soil parameters which were not mentioned in the common project before and were selected on the basis of the literature study and therefore were called 'additional parameters'.

From the parameters chosen in the first stage of the study, the following ones did not appear in any of the selected models:

- particle density
- specific surface
- exchangeable cations
- total mineralogy
- standard bulk density
- bulk density of aggregates
- swelling and shrinking of soils
- bypass flow
- air diffusion
- air permeability
- oxygen diffusion rate
- redox potential
- compaction test
- penetration resistance
- soil thin section
- morphometric characterization of thin section
- submicroscopy
- macropore continuity
- enzymatic activity
- mezo- and macrofauna.

PHYSICAL SUBMODELS

From among many existing models of plant growth and crop yield, the majority are 'weather-yield' models, which assume the optimum soil conditions. In these models it is assumed that availability of soil water and nutrients as well as soil temperature do not limit the process of plant growth and development. In agricultural practice such conditions appear very rarely. The literature review performed by the authors showed that from 251 literature items coming from the last few years, describing models of plant growth and yield, only 75 refer to the models which give consideration to soil parameters and therefore assume important impact of soil factor on actual yield. Highly developed deterministic models usually take into account soil parameters to evaluate yield loss caused by water stress.

The purpose of this study is to compare the submodels of physical processes of soil-plant-atmosphere in four chosen models of crop yield with special interest to the role of soil structure parameters in considered submodels. Table 6 presents basic information about the chosen models, their input soil parameters and soil profile division. The chosen models take into account a broad range of physical and chemical processes in the soil, plant and atmosphere and can be included to the group of complex deterministic models. In the case of CTSPAC model soil data requirements are tremendous, therefore Table 6 does not mention all of them, classifying them only into groups.

The common feature of the chosen models is that they assume the possibility of limiting the availability of soil water for plants and that they quantitatively analyse the yield loss as a result of water shortage. However important differences exist between analysed models. These differences result from different assignment of each model. In each case the goal of modelling is different:

CTSPAC (theoretical model) - the theory of water, solutes and heat transport in soil-plant-atmosphere continuum and biomass increase of idealised plant is based on constitutional physical equations;

WOFOST (versatile model) - the possibility of simultaneous analysis of development, growth and yielding of different plant species in diversified climatic and soil conditions basing on easily measurable physical-chemical quantities.

EPIC - analysis of relation between erosion and plant productivity;

CERES - simulation and forecasting of growth and yield of a given plant (maize).

CTSPAC model is a mathematical model of simultaneous transport of water solutes and heat in soil-plant-atmosphere continuum. The model is entirely basing on constitutional mathematical-physical equations. Mathematical structure of the model couples soil and plant submodels (transport through xylem and phloem). An idealised plant is divided for modelling into local regions (compartments)

Table 6. Chosen models of plant growth and yield production

Models and their origin	Soil input parameters	Description of soil profile in soil submodels
CTSPAC (Coupled Transport (of water, solutes and heat) in the Soil-Plant-Atmosphere Continuum) (Oregon State University, USA)	- soil water characteristics - soil thermal characteristics - characteristics of soil solid phase - soil and water chemical characteristics	Soil submodel is constructed for vadose zone. Soil profile is divided into 5 or more thin horizontal layers. The depth of water table is assumed constant.
WOFOST (World Food Studies) incorporated in the CGSM (Crop Growth monitoring System) for the regions of the European Union (Holland)	- moisture content of root zone - depth of ground water table - percolation rate - rate of capillary rise - runoff - surface storage - soil evaporation rate - rooting depth - rate of net influx through the lower and upper root zone boundries	The textural profile of the soil is homogeneous. Initially the soil profile consists of three layers: - rooting zone between soil surface and actual rooting depth - lower zone between actual and maximum rooting depth - subsoil below maximum rooting depth
EPIC (Erosion - Productivity Impact Calculator) (USDA-ARS, USA)	- soil water retention (pF) - bulk density and porosity - particle size distribution - pH (H_2O, KCl, $CaCl_2$) - solute, air and energy transport - depth of soil profile - albedo	Soil and management are treated spatially homogeneous. Soil profile is divided into a maximum of 10 layers.
CERES - maize (Crop - Environment Resource Synthesis) (USDA/ARS, USA)	- soil water retention (pF) - bulk density and porosity - particle size distribution - solute, air and energy transport	Up to 10 soil layers may be identified. Layers can be the horizons described in soil characterization data (with 3 constraints).

having similar structure and tissue functions. The plant is composed of 3 clusters (each having 3 leaves). All the leaves are geometrically identical. Soil is divided into 5 or more layers. The properties of root compartments can be different to simulate root density. Water movement from soil to atmosphere through roots, stems and leaves is modelled. Turgor and osmotic pressures are taken into account. Diurnal cycle of soil temperature is determined by heat balance on the soil surface. The model needs a very large number of plant, soil and meteorological input data. Therefore it is of small importance in agricultural practice, being at the same time an important theoretical attempt to present the possible broad range of phenomena connected with plant growth and development. The output data of the model are: transpiration rate, water potential in xylem and phloem, soil water content, soil temperature, the intensity of nutrients uptake from the soil, mass of nutrients accumulated in particular parts of the plant and time changes of soil solute mass. The submodels of CTSPAC are presented in Fig. 1.

Simulation model WOFOST is one of the main components of the crop growth monitoring system (CGMS) created for the whole territory of European Union. It is a versatile model, considering different soil and climatic conditions and applicable for a few arable crops: winter wheat, grain maize, barley, rice, sugar beet, potatoes, field beans, soybeans, winter oilseed rape and sunflower. As a component of CGMS, WOFOST model can be incorporated into Geographic Information System (GIS) and makes it possible to model plant production at the regional scale. The submodels of WOFOST model and modelled processes are presented in Fig. 2.

SOIL

Water transport:
- water flux to soil-plant root interface
- water flux to the interior plant root
- total water potential across the root-soil interface
- unsaturated water conductivity
- soil water diffusivity
- soil water vapour flux
- water vapour diffusity
- saturated water density in soil pores
- infiltration, soil water redistribution

Heat balance:
- heat conductivity and heat diffusivity of soil
- heat fluxes in solid, liquid and vapour phases
- average chemical flux in solid phase
- chemical flux in vapour phase
- dispersion coefficient for liquid phase
- diffusion coefficient for gas phase
- effective retention coefficient
- effective molecular diffusion coefficient
- average concentration in the sorbed phase

PLANT

Water transport:
- balance equations for liquid transport between compartments of plant

Transport and storage of chemicals in plants:
- advective bulk transport in both xylem and phloem vessels
- linear reversible sorption in each compartment
- diffusion across membranes and at the root-soil interface
- chemical partitioning of each membrane interface
- linear first order loss processes in each compartment (irreversible sorption, chemical reactions, metabolism)

Control of transpiration by the stomatal opening and closing mechanism

ATMOSPHERE

Environmental driving variables:
- water vapour deficit of the free atmosphere
- relative humidity of air
- temperature of air
- heat conductivity of air

Fig. 1. Major divisions of CTSPAC model with processes included.

WOFOST model contains some simplifications in hydrological and plant submodels to be applicable for large scales, diversified climatic conditions and different plant species. The model takes into account an impact of the rooting system development process on actual soil water content. When the rooting system achieves the maximum depth, the soil profile is described as a two layered system. Plant submodel considers only three stages of plant physiological development. In spite of these simplifications, the model considers a broad range of processes and phenomena determining plant growth, development and yield (Fig. 2).

EPIC model was created to examine the relationship between soil erosion and its

TIMER

WEATHER

Evapotranspiration (Penman)
Global radiation
Solar elevation
Day length

CROP GROWTH

Phenological development
1. Crop emergence
2. Phenological development stage
Daily assimilation
Photosynthesis
Maintenance respiration
Growth respiration
Dry matter partitioning
Leaf senescence
Root growth

WATER BALANCE

Evaporation
Transpiration (Feddes *et al.*)
Reduction of the transpiration due to water and oxygen stress
Precipitation
Percolation
Infiltration
Surface runoff
Ground water table
Root extention
Actual soil moisture content

Fig. 2. Major divisions of WOFOST model with processes included.

productivity. Therefore its hydrological submodel is well developed, and involved processes (e.g., lateral subsurface flow) and input parameters are selected in such a way, that to be applicable in erosion submodel, in which parameters limiting plant growth and yield are determined. Simulation time of hundreds of years is acceptable (using a daily time step). It makes possible to analyse relatively slow process of erosion. In spite of frequently used in other models division of soil profile into a maximum of ten layers, only the top layer thickness is constant and set at 10 mm. When erosion occurs, the second layers thickness is reduced by the amount of the eroded soil and the top layer properties are adjusted by interpolation according to how far it moves into the second layer. This idea of soil profile division and its changes determines the possibility of modelling of bulk density and temperature changes in the soil, transport of nutrients and water movement in the profile. The modelling of erosion requires taking into account the land surface slope and the slope length. The model estimates potential increase of biomass as a function of photosynthetic active radiation and daily fraction of potential increase in biomass partitioned to yield. The actual yield is determined by with consideration of growth constraints connected with erosion processes. The model can be applied for different crops. The division of EPIC model and quantities and processes included in particular submodels are presented in Fig. 3.

CERES - maize is a simulation model of maize growth, development and yield. Working with a daily time step it gives possibility to simulate the effects of genotype, weather and soil properties as well as dynamics of nitrogen changes in a plant in a field with maize growth. It is a typical user-oriented model and can be used for:

- undertaking a decision about cultivation measures during the whole year,
- analysing and planning the risk strategy with maize tillage in several years time,
- predicting yields for a large area.
- research requirements evaluation in modelling maize development and yield.

The limitation of modelling to only one plant species has some important advantages, however it enforces the necessity of specific assumptions, model construction and the choice of specific parameters and input data. Taking into account the plant specificity (the way of water extraction by roots, infiltration) in soil submodel the following rules have to be obeyed, when specifying the layers thickness in the soil profile (10 layers can be selected):

- total depth of pedon should be 2 m unless impermeable layer appears,

HYDROLOGY

Surface runoff:
1. Runoff volume
2. Peak runoff rate
Percolation
Lateral subsurface flow
Evapotranspiration
Snow melt

WEATHER

Precipitation
Air temperature
Solar radiation
Wind

EROSION

Water
1. Rainfall
2. Irrigation
Wind

NUTRIENTS

Nitrogen:
Nitrate loss in surface runoff
NO_3-N leaching
NO_3-N transport by soil evaporation
Organic transport by sediment
Denitrification
Mineralization
Immobilization
Crop uptake on N
Fixation
N contribution from rainfall
Phosphorus:
Soluble P loss in surface runoff
Mineralization
Mineral P cycling
Crop uptake

SOIL TEMPERATURE

TILLAGE

ECONOMICS

CROP GROWTH MODEL

Potential growth
Growth constrains

PLANT ENVIRONMENT CONTROL

Drainage
Irrigation
Fertilization
Liming
Pesticides

Fig. 3. Major divisions of EPIC model with processes included.

- for upper 30 cm non layer can be thicker than 30 cm.

In CERES model plant development is modelled with consideration of 9 natural stages of phonological growth, from the stage before sowing to full ripeness.

The division of CERES - maize model and the quantities and processes included in particular submodels are presented in Fig. 4.

PHENOLOGICAL DEVELOPMENT

Growth stages (9 stages from presowing to physiological maturity)

SOIL WATER BALANCE AND WATER USE BY CROP

Plant extractable soil water
Runoff
Soil evaporation
Irrigation
Infiltration
Transpiration

EXTENSION GROWTH OF LEAVES, STEMS AND ROOTS AND BIOMASS ACCUMULATION AND PARTITIONING

Root growth
Leaf area development
Light interception
Photosynthesis
Partitioning of biomass

SOIL NITROGEN TRANSFORMATIONS UPTAKE BY CROP AND PARTITIONING AMONG PLANT PARTS

Mineralization of organic nitrogen
Immobilization of mineral nitrogen
Critical nitrogen concentration
Movement of nitrate - N with percolating soil water
Denitrification
Nitrification of NH_4

Fig. 4. Major divisions of CERES model with processes included.

SUMMARY

The development of models of plant growth and crop yield should be realised in two directions. On the one hand, complex mathematical-physical models should be created, which would try to describe broadly and in detail soil, atmosphere and plant processes responsible for biomass increase, using only constitutional mathematical-physical equations. Such models are mainly of cognitive value because they develop the possibility of quantitative description of complex physical processes in soil-plant-atmosphere continuum and make it possible to understand the process of biomass creation and the factors which are responsible for it. This knowledge can enable us to control the optimum run of above mentioned process. Especially the group of soil submodels should be developed because practically always soil processes have an impact on the growth and development of plants, particularly in situation of water deficiency for plants. In case of high water deficit it is a fundamental problem in plant production. The good knowledge of physical parameters, their interactions and physical processes taking place in soil is very important, because technical possibilities and economical justification of their regulation exists, which should be done through appropriate agrotechnical treatments (improving of soil physical characteristics by proper cultivation, melioration and fertilisation).

On the other hand simplified models should be developed (the least number of input parameters), which without decreasing prediction ability, could be commonly utilised in agricultural practice.

Agrophysical metrology plays an important role in development and practical use of the models of plant growth and crop yield. The fast development of this discipline in the last several years, gives the possibility of determination of physical characteristics of modelled system and the use of monitoring systems of physical processes in soil-plant-atmosphere system for experimental verification of elaborated models. Practically, only these models can be applied which are equipped in representative physical characteristics and were positively experimentally verified for particular plant species and classes of climatic and soil conditions. Gradually developed investigations concerning the creation of data base on computer data carriers and in the form of maps are the base for application of the models for large areas, taking into account predicted climate changes.

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