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A preliminary study on simplified simulation model of spring wheat growth

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Abstract—In the model developed in this paper, taking the characters and requirements of meteorological services into account, some conventional meteorological observations which are easy to be obtained have been chosen, and mathematical equations describing micro-growth processes of crops have been established on the basis of the field experiments, laboratorial analysis and computer's modelling tests with time interval of ten-days for several years (1987–1989), in accordance with the known biological and physical rules and corresponding reference literatures. It is a preliminary simplified simulation model of spring wheat growth in optimal water and nutrient conditions. The field experiments show that simulation results of this simplified model are satisfactory. The potential operational application and theoretical sense are significant in the meteorological forecast of yield and in the assessment of influences of climatic change on agriculture.

Keywords: growth simulation; simplified dynamic model; spring wheat.

INTRODUCTION

Crop-soil-weather can be considered as a closed growth-environment system. Analysing the energy conservation and matter distribution in this system, describing these processes by use of mathematical functions and then developing the simulation model of crop growth can not only illustrate the interaction between crop growth, development and yield formation and weather-environmental conditions, but also give scientific basis for developing dynamic weather yield prediction model and dynamical monitoring.

The study on simulation model of crop growth has been already carried out for many years in Holland(The Netherlands), USA and USSR(Penning, 1982; Keulen, 1986), and has been just begun in China(Feng, 1987; Huang, 1986). At present, most of these models have not been put into practice, while it is difficult to obtain the required daily or hourly meteorological and biological data as input data.

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In the model developed in this paper, taking the characters and needs of meteorological services into account, some conventional observations which are easy to be obtained in weather stations have been chosen, and mathematical equations representing and describing main growth processes of crops have been established on the basis of field experiments and previous studies. Then a preliminary simplified simulation model of spring wheat growth has been developed. In a certain precision it can simulate the crop growth, development and yield formation dynamically, and to be used in the meteorological forecasts of yield and in the assessment of influences of climatic change on agriculture.

CONCEPT AND METHOD

Plant converts the solar energy into biomass through photosynthesis. In this process CO_2 is converted into carbohydrates (CH_2O). At the same time the carbohydrates (CH_2O) formed during assimilation is partially consumed by the growth and maintenance respiration. Here "Growth" is defined as the formation of structural material for plant, and "Maintenance" is meant as the living function of plant to be under way. And the remainder is dry matter reserve. Then, the dry matter is distributed to each organ of plant according to specific biological rule. In summary, it is the whole process of crop growth, development and yield formation. The model studied in this paper is designed based on the above concept and the field dynamic observational experiments for spring wheat have been conducted at agrometeorological experimental station in the Inner Mongolia Meteorological Institute for several years(1987–1989). The field observations and measurements of biological elements, soil moisture and the others have been carried out for each ten days. Combined with the meteorological observations, the various simulation parameters have been determined by means of the laboratorial analysis and computer-based numerical test, a simplified dynamic simulation model of spring wheat growth has been established primarily, and the related verification has been also made.

As crop growth depends on environmental climatic conditions, water and nutrient supplies, diseases and pests and so on, so for the first stage of study it is assumed that the spring wheat growth under optimal water and nutrient conditions, approximately homogeneous distribution of temperature and wind speed in crop canopy and well-supplied CO_2. The studies on dynamic simulation model of spring wheat with actual water-nutrient and other conditions(no optimal) will be conducted in times to come for the second and third phases of studies.

In general, there are two kinds of parameters in the simulation model, i.e., the numerical parameters which do not change with time and the functional parameters changed with times. For instance, the rate of maintenance respiration, the conversion efficiency of growth respiration and so on belong to the former. Considering the limitation of experiments in this paper the common values written in most of previous studies are adopted as the numerical parameters.

However, the functional parameters which change in the whole crop growth process, such as the distribution function, are determined by field experiments and numerical simulation tests.

In the model, the accumulation of dry matter stands for crop growth. The numerical integration method is used in simulation programm. It means that if the sum of dry matter is defined as the state variable, it can be calculated and accumulated step by step until the end of growth period. As the above illustrated, in order to put in practice, ten-days is adopted as time interval (Δt).

Agrometeorological research and practice for a long time show that accumulation and distribution of plant dry matter are closely related to the development rate of plant. However, the later is dependent on the rate of effective accumulated temperatures. Therefore, in the model the time variable is expressed by biological time scale instead of the calendar time scale. In other word, that the development stages of wheat, are represented by the ratio of measured accumulated temperatures to the required accumulated temperatures from beginning of growth to flowering and from flowering to maturity and simply named the biological time(DVS), being of time variable in the model.

The simplified simulation of spring wheat growth consists of two parts: the simulation of dry matter increment and the simulation of dry matter distribution. The former includs the simulation of elementary physiological processes, such as photosynthesis, respiration, dynamic increment of leaf area index and so on, and the later involves the simulation of dynamical balance of energy and matter in processes of dry matter distribution and conversion and grain formation.

SIMULATION OF DRY MATTER INCREMENT

Photosynthesis

The calculation of dry matter production is based on the determination of gross CO_2 assimilation rate. In the model assimilation rates of a closed canopy on completely clear days and completely overcast days are obtained from the calculation values worked out by de Wit and then corrected by Goudriaan and van Laar(Goudriaan, 1978), i.e., according to the response curve of leaf CO_2 assimilation to light, the optical characters and space distribution of leaves and so on, and the potential assimilation rates of a closed canopy on completely clear days (Pcl) and completely overcast days (Pov) can be calculated with different latitudes and time periods in optimal water and nutrient conditions. Then the actual rate of CO_2 assimilation of canopy (Ps) is corrected by weighting factor (f) of the specific radiation status. It can be expressed by the actual fraction of the specific overcast day:

$$Ps = fov \times Pov + (1 - fov) \times Pcl. \tag{1}$$

The weighting factor of actual overcast day (fov) can be calculated by the following equation:

$$fov = (Sc - Sa)/0.8 \times Sc, \tag{2}$$

Where Sc is the global radiation of clear days and Sa is the actual (measured) global radiation.

The light interception of plant should be also corrected in accordance with the dynamic growth of leaf area, because the soil might not be covered completely in the whole growing season.

$$f1 = 1 - \exp(-K_0 \times LAI). \tag{3}$$

In Equation (3), $f1$ stands for corrected factor of canopy leaf area, LAI is actual leaf area index, and K_0 represents extinction coefficient, the changes of which with altitude in crop canopy, as approximation of first degree, generally are omitted (Yin, 1959; Penning, 1982). So, it can be assumed as constant. After corrections the assimilation product (P) can be written as:

$$P = A \times f1 \times Ps. \tag{4}$$

In Equation (4), A is the proportional coefficient of assimilation product (carbohydrate) and carbon dioxide(CO_2) gram-molecule weight.

The photosynthesis of plant is conducted under a certain temperature conditions. The optimal temperatures of photosynthesis written in different reference materials are not the same. But most of them fall in range of 18–25°C (The Teaching and Research Group of Agrometeorology, 1982; Research Office of Photosynthesis, 1981), while the maximum temperature of photosynthesis are the 40–50°C. Considering the climatic conditions of specific experimental site, where the temperature in warmest month of summer is not higher than the above described maximum temperature generally, and therefore, the temperature influence coefficient of photosynthesis (FT) in this model can be written by:

$$FT = \begin{cases} T/T_0 & T < T_0 \\ 1 & T \geq T_0, \end{cases} \tag{5}$$

where T_0 is the optimal temperature of photosynthesis, T is the actual temperature. Temperature (T_0) is calculated by numerical testes on computer.

Respiration

As the above described, a basic biological rule of plant growth is that the assimilation product is partially consumed by the growth respiration (Rga) for formation of new structural material of plant and the maintenance respiration (Rma) for keeping the plant living function respectively.

$$Rt = Rma + Rga, \tag{6}$$

where Rt is the gross respiration consumption, Rma and Rga can be estimated by following equations respectively:

$$Rma = Rm \times W, \tag{7}$$

$$Rga = (1 - CVF) \times (P - Rm \times W). \tag{8}$$

In these equations, W is the dry weight of plant, CVF stands for the efficiency coefficient of primary photosynthetic product transforming into the structural material of plant (in concrete calculation, it is assumed that $CVF = 0.7$g dry matter/g carbohydrate), and Rm is the maintenance respiration rate, which is drawn from reference literature(Penning, 1982) and equals to 0.015g. carbohydrate/g dry matter/day. This is the maintenance respiration rate at standard temperature $-25°C$ (Rm(st)), and so must be corrected by observed actual temperature, that is

$$Rm = Rm(\mathrm{st}) \times Q_{10}^{(T-25)/10}, \tag{9}$$

where Q_{10} is temperature influence coefficient (in general, $Q_{10} = 2.0$), and T is the observed temperature.

Obviously, in Equation (8) the term of (1-CVF) represents the energy consumption rate in conversion process, i.e., the growth respiration rate.

Dynamic growth of leaf area

Green leaf is a main photosynthetic organ of plant and the intensity of photosynthesis depends on the leaf area index (LAI). So the later is a key factor in modelling crop growth.

The field experiments show that before earing, in general, the green leaves grow slower in the beginning, then faster and faster and slower once again in the latest phase of vegetation period of spring wheat (DVS <0.9), thus the growth process of leaves (LAI) may be simulated by logistic growth function:

$$LAI = \frac{5.168}{1 + \exp(3.7849 - 7.2395 \times DVS)}, \quad (DVS < 0.9) \tag{10}$$

where the correlation coefficient $R = -0.9816$, and residual standard deviation $S = 0.264$(Fig.1); and after earing ($DVS > 0.9$), the colonial leaf area index decreases rapidly, and its better fitting can be achieved by following linear function:

$$LAI = 9.7636 - 4.8804 \times DVS, \quad (DVS > 0.9) \tag{11}$$

where $R = -0.9423$, $S = 0.508$ respectively (Fig.1).

It should be noted that in simulative procedure of the dynamic growth of leaf area, the limited life-span of green leaf is another important effecting factor. So the weight of yellowing-death leaves has to be estimated and deducted. In the reference (Penning, 1982) the senility of

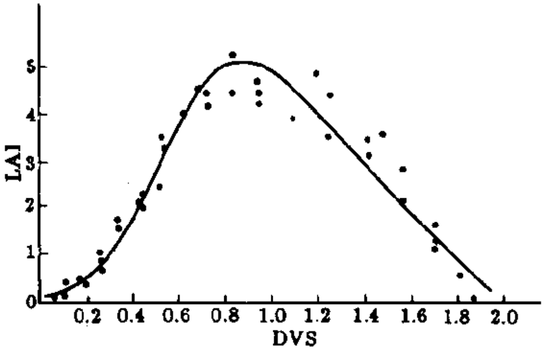

Fig.1 The variation of *LAI* with *DVS*

leaf is taken into account only after flowering, and its death rate is assumed as a constant. Our field experiments show that leaf yellowing-death appeared in the earlier vegetation stages and the yellowing-death rate of leaves is characterized by exponential function with DVS (Fig.2), from $DVS > 0.5$ until $DVS = 1.9$ (the later period of yellow-maturity), especially, increased at a great rate after flowering (i.e. from $DVS > 1.0$):

$$DR = 0.005231 \times \exp(2.7525 \times (DVS - (1 - k)), \tag{12}$$

where DR is yellowing-death rate of leaves, k is a coefficient corrected by temperature (Wang, 1990). Furthermore, such a character can be used to correct LAI.

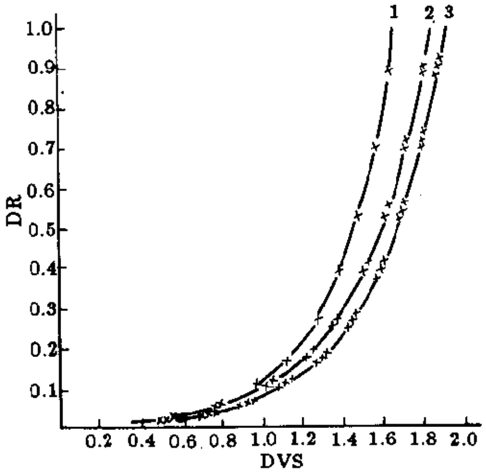

Fig.2 The variation of yellowing-death rate of leaves with *DVS*
1. sown later 2. sown at optimal date 3. sown earlier

Simulation of dry matter increment

Based on the above submodels, the equation of dry matter increment (dw/dt) of plan can be expressed as:

$$dw/dt = CVF \times (P - Rma \times W). \tag{13}$$

SIMULATION OF DRY MATTER DISTRIBUTION

The increment in gross dry matter of the crop is distributed to the various organs(root, stem, leaf and grain) at a certain proportion. In addition, the storage organ may be formed not only from current photosynthates but also from plasticity matter (carbohydrates and proteins and so on) which have been stored temporarily in vegetative parts of plant and are redistributed during the reproductive stage. So, the growth of crop organs is based on the distribution and transference of assimilation products. However, in the model of the most of above mentioned references (Huang, 1986; Penning, 1982) only the former, and in some literatures (Feng, 1987) also the later, have been taken into account. Evidently, ones believe it to be rational that both the distribution and transference of assimilation products should be considered comprehensively, and thus represented by the following:

$$Fi = \Delta wi/\Delta w, \tag{14a}$$

$$FTi = \Delta wi/wi. \tag{14b}$$

In the formula (14a), $i = 1, 2, 3, 4$, stands for foot, stem, leaf and storage organ (grain), respectively; Fi is a distribution function of assimilation products of i-th organ, the value of which depends on the development stage (DVS); Δwi is the increment of i-th organ growth; Δw is the gross increment of crop growth. After flowering $F_4 = 1$, $F_1 = 0$, $F_2 = 0$ and $F_3 = 0$. In the formula (14b), $i = 2, 3$, i.e., stem and leaf, FTi is the transference coefficient from stem and leaf to storage organ(grain); Δwi is the growth increment of stem and leaf (negative value); wi is the known weight of dry matter of stem and leaf. The transference of assimilation products only occures in certain development stages, while distribution of assimilation products to stem and leaf stops, and the plasticity matter stored previously in stem and leaf is partially transfered to the storage organ (grain). The values of transference coefficients are related to the weight of stem and leaf, and vary with DVS. So, in the model of this paper, the growth increments of storage organ are expressed by sum of both the above mentioned parts (distribution and transference):

$$W4 = F4 \times W + \sum_{i=2}^{3} FTi \times Wi. \tag{15}$$

According to the analysis of experimental data for spring wheat, it is found that when $DVS > 0.9$ (ear initiation stage) the partial storage matter in leaves begins to be outflow; and while $DVS > 1.2$ the outflow of stem appears. Though the time of stem outflow is some later than that of leaf, but the volume of outflow is much more than that of leaf.

A part of experimental results in 1987–1988 are shown in Fig.3, and the rest are ommitted here.

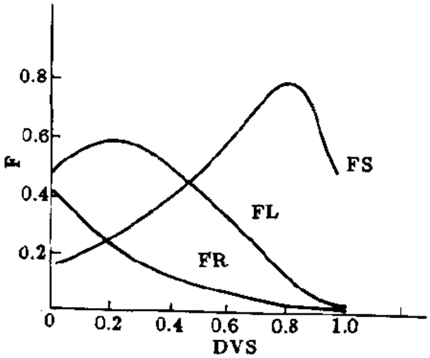

Fig.3 The distribution function of dry matter of organs
(root-FR, leaf-$F1$, stem-FS)

RESULTS AND DISCUSSION

1. After the data about geographical latitude, the required accumulated temperatures of spring wheat, initial weight of canopy, and then mean temperatures and observational global radiation are put into computer ten-days by ten-days, the simulated gross dry matter weight of canopy as whole and of each organ as well as the leaf area index are obtained. As a result of simulation, the correlation coefficients between calculated values of ten-day's gross dry matter weight and measured ones for every sowing time of spring wheat are over 0.99, and over 0.93 between the same two ones for organs except one being 0.89 in experiment of 1987. The avarage relative error between the ten-day's gross dry matter weight and measured ones is equal to 13.4%, the same error between the simulated gross dry matter and measured ones of crop as whole equals to 8.4%. The verification of a set of sampling data in 1989, for example, shows that the mean relative error is 10.6% for ten-day's gross dry matter, and 7.4% for the crop as whole in the end of growth. And corresponding correlation coefficients are equal to 0.9991 for the ten-days gross dry matter and over 0.96 for various organs, except leaf being 0.90. So it is to be demonstrated that the fitting results of the above simplified simulation models are satisfactory (Fig.4 and 5) and this simplified model as whole can response the change tendency of dry matter accumulation in the growth process of spring wheat.

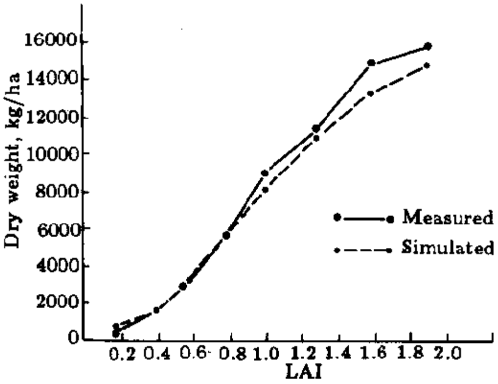

Fig.4 The modelling curves of gross dry matter weight (in 1989)

From Fig.4 and Fig.5 it can be seen that calculated values are similar to measured ones and the trend of accumulated course of dry matter can be basically represented.

2. This model is only a preliminary attempt as a first phase to develop a simplified simulation model of spring wheat growth. Because of the less factors involved, the longer time interval and also the inhomogeneity of field growth situation as well as errors of sampling, the

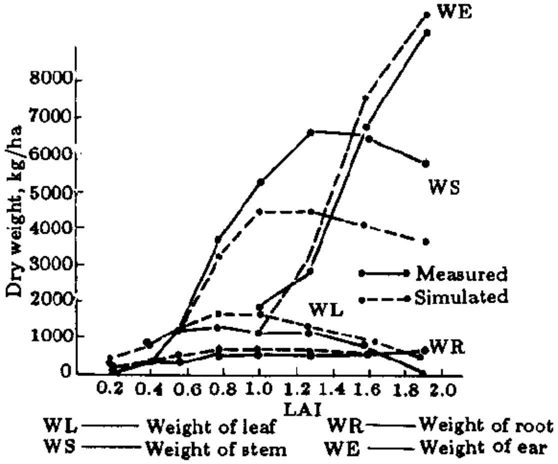

Fig.5 The modelling curves of dry matter weight of various organs (in 1989)

error in simulation is inevitable (Table 1). But even so, the simulated results can also describe the dynamic accumulated course of dry matter, and evidently have advantages in less data required, convenience of operational uses and no more computer times and so on. Certainly, it is necessary to make experiment once again in field, and then modify the parameters, improve the properties of model and increase the stability of simulation.

Table 1 Comparison between simulated and measured values

Samples	Measured total weight, kg/ha	Simulated total weight, kg/ha	Relative error, %	Measured grain yield, kg/ha	Simulated grain yield, kg/ha	Relative error, %
1988(1)	14074.5	13617.9	3.2	6583.5	6568.5	2.2
1988(2)	12861.9	13631.6	5.9	6922.5	6568.5	5.1
1988(3)	15771.6	13624.2	12.4	7662	6562.5	14.4
1988(4)	15525.6	13152.4	15.2	7591.5	6028.5	20.6
1988(5)	12926.7	12231.6	5.4	6873	5373	21.8
1987(2)	19383.1	15263.5	13.0	9570	6955.5	27.3
1986(2)		14466.1		6589.5	6870	4.3
1989(3)	15650.5	14498.2	7.4	8302.5	6730.5	18.9

3. Undoubtedly, many and many other physiological processes and environmental factors affecting the crop growth and development should be considered and carried out in a complete dynamic simulation' model of crop growth system. Therefore, the simulation model of crop growth under actual water and nutrient conditions will be studied and developed in the further programs as the second and their phases of this research project.

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