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REGULAR ARTICLE

SIMULATING PHOTOSYNTHESIS, RESPIRATION AND DRY MATTER PRODUCTION IN ANNUAL CROPS

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SUMMARY

Crop simulation model, mathematical exhibition of physiological different process of crop growth and development and its response to environmental factors. Then the aim of this study is to provide a computer model for simulating photosynthetic, respiration and dry matter production in annuls crop. In this model daily gross canopy photosynthetic rate is a fraction of the maximum photosynthetic rate of a fully developed canopy at light saturation. For calculation of that, leaf area index based on the relative length of the four different crop development stage is calculated. Leaf area index, minimum and maximum daily temperature and daily radiation as model inputs were considered. After calculating gross photosynthetic rate, growth and maintenance respiration waste minus its and daily dry matter is calculated based on conversion efficiency coefficient. Sunflower data is used for testing of model. Regression of simulated over observed dry matter yield and leaf area index showed a good correspondence between predicted and observed dry matter yield and leaf area index. R2 for both dry matter yield and leaf area index were more than 0.95 suggesting that the model was successful in growth and yield crop.

Keywords: dry matter, leaf area index, photosynthesis, respiration.

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1. Introduction

Crop simulation models, mathematical exhibition of physiological different process of crop growth and development and its response to environmental factors. Building and application of dynamic simulation models and its predicting are powering tools for maximizing scientific tries use efficiency [1]. In the world during the last two decades, crop modeling has become a major research tool in agriculture as in other areas of plant production. Models offer a conceptual framework for the organizing research and instruction. Therefore models can be very useful in teaching students crop production principles. This includes concepts on how plants respond in general to environment and management, and how crop species differ. In addition, models can be very useful in demonstrating interactions among processes or components of crop production systems. Models can help scientists, engineers, students and growers of crop with capability of exchange and control of process and reducing process time [2]. Photosynthesis process is base of plant production. Therefore first step crop growth modeling is Photosynthesis process modeling [3]. The aim of this study is to provide a mechanistic model for simulating photosynthesis, respiration and dry matter production in annuls crop. This model can be used as an instructional and research tool for analyzing plant and environmental limitation factor on photosynthesis and respiration.

2. Materials and methods

In this model daily time period is used for simulating process. In this model daily leaf area index (LAI) simulation is based on the LAI at maximum growth rate and the relative length of the four different crop development stages [4]. For calculating daily gross photosynthesis (Pg) is used curve rectangular hyperbola photosynthesis reaction to radiation [5]. Then the loss of respiratory function of temperature is deducted from gross photosynthesis and net photosynthesis is obtained. Daily production of dry matter based on its compounds and using the coefficient of conversion efficiency of daily net photosynthesis is achieved.

Leaf area index

In this model approach was followed, based on the LAI at maximum growth rate and the relative length of the four different crop development stages, defined by the FAO and the International Institute for Applied Systems Analysis [4]. Thermal time controls these different crop development stages. Hence, thermal time concept was used to quantifying development stage, with a base temperature (Tb) and critical temperature (Tc) as:

$$\begin{aligned} DTT &= Tb && \text{if } T < Tb \\ DTT &= T - Tb && \text{if } T > Tb \\ DTT &= Tc && \text{if } DTT > Tc \end{aligned} \qquad (1)$$

Where DTT is the thermal time each day (˚Cd) and T is average daily temperature. Thermal time (TT) was calculated by accumulating DTT after emergenc.

With respect to leaf growth rate, four growth stages have been distinguished.

Stage 1: This stage, starts from emergence to the end of the vegetative stage, is referred to the period of fast linear growth during which the LAI increases at a constant rate and calculated by below equation:

$$LAIi=(LAI\,max / TT1)*(TTi) \text{ if } TTi \le TT1 \qquad (2)$$

Where LAImax equals the LAI at maximum growth rate and TT1 represents the accumulated thermal time from emergence till the end of first stage.

Stage 2: From this stage, more and more assimilates are used to produce reproductive organs, and leaf development continues with a constant trend, but reduces until midseason when the LAI at full canopy development (LAIfull) is attained. The LAIfull has been estimated by LAImax + 0.5. Consequently, the rate which the LAI increases during this linear lag period equals to:

$$LAIi=(LAIfull-LAImax)/(TT2)*(TTi)+LAImax \qquad (3)$$

$$\text{If } TT1 \le TTi \le TT2$$

Where TT2 represents the accumulated thermal time from emergence till the end of stage 2.

Stage 3: Leaf growth stops from this stage until all assimilates are used for the development of flowers and seeds. To the end of the stage 3, all leaves are actively participating in this biomass production, and the LAI remains constant.

$$LAIi = LAIfull \text{ if } TT2 < TTi \le TT3 \qquad (4)$$

Stage 4: Start of stage 4 or the maturation stage marks the leaf growth stage of exponential decay characterized by an exponentially decreasing leaf area due to leaf senescence. Penning de Vries and van Laar [6] estimated the relative leaf death rate during this stage at 3% per day:

$$LAI(i)=LAI(i-1)-(0.03*LAI(i-1)\text{if } TT(i)>TT3 \qquad (5)$$
$$\text{If } TT(i) = GTT \text{ then End}$$

Where LAIi (m2 m-2) and LAI(i-1) (m2m-2) are the actual LAI and the LAI of the previous day, respectively.

Gross photosynthesis

In this model first daily gross canopy photosynthesis (kg $Co_2m^2d^{-1}$) is calculated as follows [8]. In fact daily gross photosynthesis is a fraction of the maximum photosynthetic rate with full canopy.

Pg = Pmax * *f*(x)* LAI

Where Pmax equals the maximum photosynthetic rate at light saturation (kg $Co_2m^2s^{-1}$). Amount of Pmax is different in between species and genotypes. Estimates of Pmax at a standard temperature of 20° C are given in table 1 for four types of crop [9]. The function value *f*(x) ranges from 0 in darkness to 1 at saturating light intensities, when the maximum rate of photosynthesis Pmax is reached. X also is dimensionless group as follows:

X = (QE * I) / (Pmax * LAI)

In fact x ratio of photosynthetic rate at limiting light to photosynthetic rate at light saturation. QE for the initial light use efficiency and I for absorbed radiation per leaf area. Amount of QE is 12.9 (10^{-9} kg $Co_2.J^{-1}$) for full canopy [8].

Different functions for f(x) is introduced. One of the most general functions for this relation is the non-rectangular hyperbola [6]:

$f(x) = \{1 + x - \sqrt{((1+x)^2 - 4\,x\,\theta)}\} / 2\theta$

The parameter θ regulates the shape of this function. θ varies between 0 (leading to the softly rounded rectangular hyperbola.) and 1 (leading to the sharp-shouldered Blackman response.). For the intermediate value of 0.7, the shape of the function is very close to the widely used negative exponential function as follows:

$f(x) = 1 - \exp(-x)$

To express daily gross photosynthesis rate (GP) in kg CH_2O ha^{-1} d^{-1}, the ratio of the molecular weight should be taken into account:

$GP = 30/44\ Pg * 10^4$

Respiration

Respiration is an important part of the C budget of crops because it is responsible for the loss of CO_2 from plant cells. High-energy compounds are broken down through two pathways: photorespiration and dark respiration. Photorespiration of C3 crops has already been accounted for by a lower photosynthetic rate at light saturation. There is no photorespiration in C4 plants. Irrespective of their photosynthetic system, all green plants undergo the process of dark respiration in which atmospheric oxygen is used by plants to convert carbohydrates into CO2 with and water, with the simultaneous liberation of energy. Plants use this energy to build more complex molecules from the initial products of photosynthesis. Dark respiration can be considered at two levels [8]: maintenance respiration and growth respiration.

Maintenance Respiration

Maintenance processes in plants consist of synthesis of degraded proteins and maintenance of ion gradients across cell membranes. Both processes require a constant supply of energy, delivered by the maintenance respiration process [7].

As the maintenance process is mainly related to protein content, its calculation can be based on the protein content of the tissue. Estimates of the relative maintenance respiration rate, Rm, at a standard temperature of 20 are given in Table 1 for four types of crops. Temperature, the most important factor, usually stimulates the maintenance process by a factor of 2.0 per 10ºC temperature increase [10]. To take into account the impact of temperature, the maintenance respiration has been calculated as follows [10]:

$MR = 2^{(t\,mean - 20)/10} * Rm * GP$

Where MR represents the daily maintenance respiration rate (kgCH_2O ha^{-1} d^{-1}) and tmean represents the mean daily temperature (ºC).

Growth Respiration

The conversion of the primary photosynthates into structural materials (carbohydrates, proteins, lipids, lignin, organic acids, and minerals) requires substrate for building materials and energy for synthesis of the product, the transport of sugars, and the uptake of N and minerals. In fact growth respiration, which is weight of dry matter formed per unit weight of assimilates. For in order to it can be used growth conversion efficiency (Eg) has been proposed by Pening de Varies and Van Laar [7]. The amount of growth conversion efficiency depends on the chemical composition of the biomass formed (Table 1).

Net photosynthesis

Daily net photosynthesis (kg CH_2O $ha^{-1}d^{-1}$) is calculated as follows:

NP = GP - MR

Dry matter production

Daily dry matter production (CGR, kg ha^{-1} d^{-1}) is achieved by multiplying growth conversion efficiency at daily net photosynthesis as follows:

$CGR_{(i)}$ = Eg * NP = Eg * (GP – MR)

Therefore accumulated dry matter (DM, kg ha^{-1}) for each day is calculated as follows:

$DM_{(i)} = DM_{(i-1)} + CGR_{(i)}$

Where $DM_{(i-1)}$ represents the accumulated dry matter at previous time step.

Table 1. amount of QE, Pmax, Rm and Eg at standard temperature of 20º C in crop types.

Crop types	QE (10^{-9} $kgCO_2J^{-1}$)	Pmax (10^{-6} $kgCO_2m^{-2}s^{-1}$)	Rm (%)	Eg ($kgDMkg^{-1}CH_2O$)
Root and tuber	12.9	1.42	20	0.75
Cereals	12.9	1.56	20	0.70
Protein rich	12.9	0.85	20	0.65
Oil reach	12.9	0.83	20	0.50

Environmental characteristics

University of Mohaghegh Ardabili research station was located at 36° N and 37° E and at an altitude of 1200 m. The soil texture in study site was loam silt. Average daily temperature varies between 14.4 and 34.4° C and also average daily radiation varies between 9.4 and 28.09 $Mj.m^{-2}.day^{-1}$.

Crop characteristics

In order to achieving of crop characteristics (length of growth duration, length of relative growth development stage and maximum leaf area index) Armaviruski cultivar cultivated in University of Mohaghegh Ardabili research station on 30 April in 2008. Length of growth duration lasted for 121 day. First growth stage characterized by from emergency until full ground cover lasts for 60 day. Second and third stage includes flowering and seed formation, last for 30 day. During a 31 day forth growth stage, the seeds ripen and dry. For calculating LAI and CGR, four plants were sampled each 15 day. Full canopy developed had leaf area index equal 3.5.

Test of model

For testing model, the capability of the model was determined to predicting of leaf area index and accumulated dry matter production. In order to determining capability of model, leaf area index and plant dry matter were measured each 15 days intervally. Then by using of model was generated same data for like days. Finaly coefficient determination (R^2) was determined for measured and simulated data by linear regression.

Results and discussion

Outputs of model are daily leaf area index, gross and net photosynthesis, maintenance respiration, crop growth rate and accumulated dry matter.

Measuring and predicting leaf area index values are showed in figure1. Armaviruski had LAImax and LAIfull equal 3 and 3.5 respectively. Predicting daily gross photosynthesis and intercepted radiation value at during cycle growth crop are showed in figure 2&3 respectively.

Figure 4 show maintenance respiration and daily mean temperature at during cycle growth crop. We had not measured data For testing outputs includes daily gross photosynthesis and maintenance respiration.

Predicting CGR and accumulated dry matter values with along measuring accumulated dry matter are showed in figure 5. As we had not measured data for photosynthesis rate, for testing model, the capability of the model was determined to predicting of leaf area index and accumulated dry matter production. In order to determining capability of model, leaf area index and plant dry matter were measured each 15 days intervally. Then by using of model was generated same data for like days. The trends in measured and simulated values for leaf area index and accumulated dry matter showed a good agreement at different growth stage. This suggests that the relationships and parameters used in the model described the growth and yield of sunflower (cv. Armaviruski) adequately.

Regression of simulated over observed dry matter yield and leaf area index showed a good correspondence between predicted and observed dry matter yield and leaf area index (figure 6&7). R^2 for both dry matter yield and leaf area index were more than 0.95 suggesting that the model was successful in growth and yield crop. This model can be used to predict growth and yield Sunflower cultivar Armaviruski in the other locations. In addition by using of this model can be evaluated plant processes as photosynthesis, respiration, crop growth rate and dry matter production. Finally this model can be used as an instructional and research tool for analyzing plant and environmental limitation factor on photosynthesis and respiration.

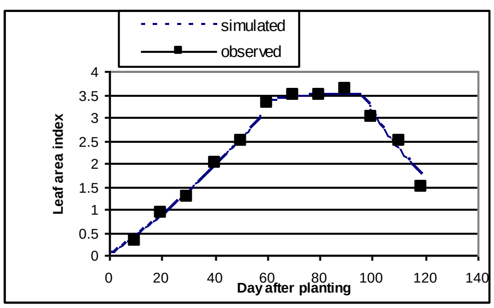

Fig. 1. Time trends in simulated (--) and observed (•) leaf area index.

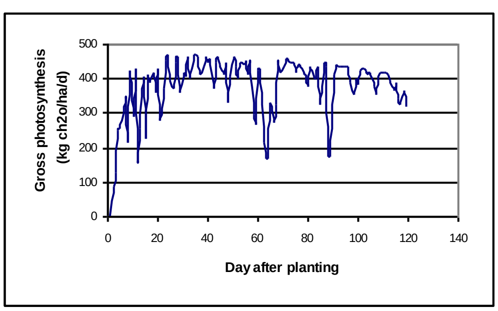

Fig. 2. Time trends daily gross photosynthesis in during the growth cycle crop

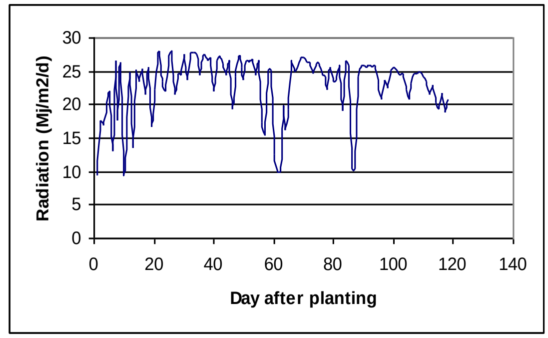

Fig. 3. Average daily radiation in during the growth cycle crop

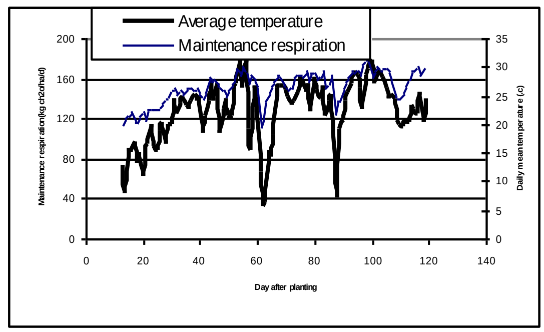

Fig. 4. Average daily temperature along with daily maintenance respiration

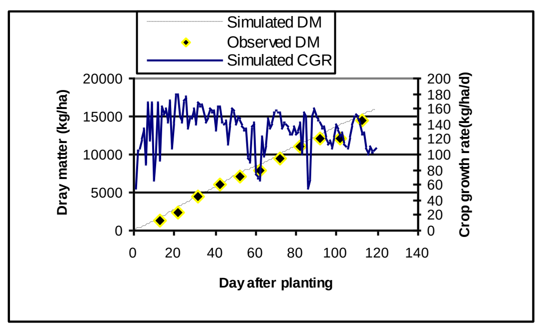

Fig. 5. Time trends in simulated (--) and observed (•) dry matter and crop growth rate (__).

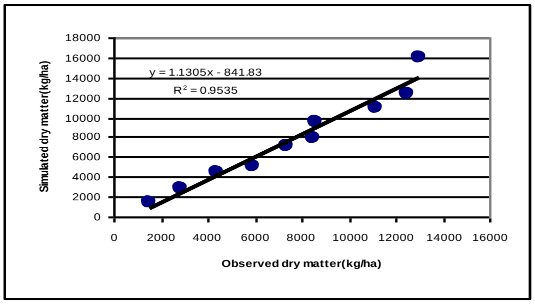

Fig. 6. Linear relationship between the simulated and observed dry matter.

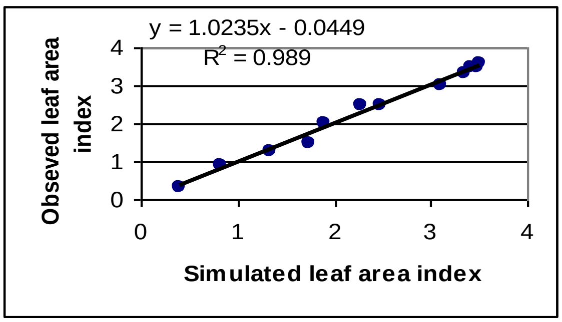

Fig. 7. Linear relationship between the simulated and observed leaf area index.

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