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Contribution of Mathematical Model for the Development of Sustainable Agriculture

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ABSTRACT

This paper briefly describes the contribution of mathematical science in the development of rice growth model and outlines the potential uses of this kind of model for sustainable agricultural development. The model is a mechanistic model that simulates rice growth based on the interactions amongst rice characteristics and the various underlying environmental conditions. The model is very useful to researchers, extension workers and policy makers in their works. In research, it enables researchers to integrate knowledge with various disciplines in a quantitative manner thereby helping in understanding the complex behavior of agricultural systems on the basis of underlying processes. In field, it may be used to support problem-solving and decision-making processes. To policy maker, the model helps to predict the future outcomes based on the proposed current set of scenarios.

INTRODUCTION

Sustainable agricultural development seeks to balance three long-term goals, growth in economy, friendlliness to environment and acceptance of people. The right blend of these goals is indispensable for food security (Fischer 1998). Some of the questions that need to be immediately answered in dealing with food security are:

- How can productivity be increased to meet the growing demands for food while maintaining healthy environment?
- Which technologies are efficient, economically viable and environmentally appropriate for a farmer endowed with specific resources?
- How can public policy be formulated to help ensure that agriculture will meet current and future needs?

To look for appropriate answers, agricultural community must have a detailed understanding of agricultural systems and their interactions with other segments of society.

Traditional agricultural research conducted along reductionist lines is not adequate for providing the understanding necessary to address the broad issues outlined above, nor for packaging the information in a way that a wide variety of users can easily access and interpret. A holistic research approach is necessary for understanding sustainability and the effects of changing external influences on farming systems. A mechanistic crop simulation model is an essential tool for carrying out holistic research. This model requires systematic understanding of various complex biological processes that are involved in farming activities. This can be achieved through proper analysis of defined system boundaries and system components, developing models of those components, and integrating them for studying the behaviour of the entire system (Rabbinge et al. 1994).

Mathematical model is a fundamental tool for development of mechanistic crop simulation model. It lets complex biological systems in agriculture to be analysed and understood (France and Thornley 1984). In this paper, the application of mathematical models in the development of rice growth will be highlighted. The various benefits of this model in research for formulating sustainable agriculture will also be pointed out.

Development of rice growth model

Model description

Rice growth model is simulated on the basis of various biological and ecological processes. The major processes are phenological development, photosynthesis or CO_2 assimilation, transpiration, respiration, partitioning of assimilates to various organs, and dry matter production (Figure 1). Detailed descriptions of the model can be found in Kropff et al. (1994). In short, total daily rate of canopy photosynthesis is calculated. Then the requirement for respiration is determined. By subtracting total daily photosynthesis canopy with respiration and maintenance requirements, the net daily photosynthesis is determined. The net photosynthesis then is converted to dry matter that is partitioned among the various plant organs. Mathematical models are used in almost all steps of these calculations either within the component or between the components.

Roles of mathematical model in modeling rice photosynthesis

Mathematical models are basically a simplified description of a system, built to help us better understand the operation of a real system and the interactions of its main components. The systems can be in the same level or at different hierarchies. As example, details on how mathematical models are used in simulation total daily rice photosynthesis are explained. It is a complex process and the driving force behind simulation of rice growth.

The calculation procedure is schematically represented in Table 1. The three most important factors involved are: 1) the photosynthesis light response curve of leaves, 2) the light distribution within canopies, and 3) environmental factors affecting photosynthesis. These are presented here and together with demonstration of how they can be integrated and used to yield totals for each day of canopy photosynthesis under various conditions. At least four mathematical equations are used in the procedures. The most important mathematical model is light response curve (equation 1). It is used to calculate photosynthesis of individual leaves at each layer. It is a function of initial slope (ε), the asymptote (Y_m), and amount of light (I_L). The amount of light at each layer is determined by equation 2. Radiation fluxes attenuate exponentially within canopy with increase in leaf area from the top downwards. The effect of environmental factors are modeled through equation 3 (effect of ambient CO_2 concentration) and equation 4 (effect of leaf nitrogen content). Both factors affect the parameter Y_m.

Model evaluation

The performance of the model was evaluated by comparing the outputs of the model with the actual data. The parameters used in the simulation model were obtained from a detail field experiment conducted on local rice variety (Mohd Norowi 2001). Some of measured parameters were, Y_m, dry mater of various rice growth components, leaf area index (LAI), and leaf nitrogen content. Local weather data were used in the simulation. The outputs used in the comparison are LAI, total above ground dry matter (WAG), weight of panicles (WPA), weight of stems (WST), weight of green leaves (WLVG) and weight of dead leaves (WLVD). Statistically, test for goodness of fit for all rice growth components indicates that simulated values are not in conflict with the observed values (Table 2).

Application of the model

Rice growth model can be used for different categories of activities. In the first place, they can be used by researchers to guide and support their research. Secondly, the model can be used by applicators to assist problem solving and decision-making. In the third place the model can be used in formulating a policy by policy-makers. A brief description is given for each category.

Agricultural research and development

Holistic approach

One of the most spectacular aspects of crop modeling so far is its bridge function between basic disciplines (i.e. plants physiology, agronomy, soil physics, pest science, mathematics etc.). Knowledge from the basic disciplines is quantified and used to explain the dynamics of crop growth and crop production in relation to its environment. Well-developed model and tested models can be used to analyze the backgrounds of agricultural problems and to identify possible solution (Rabbinge 1986).

Extrapolation

In general, model can be a strong tool to extrapolate research findings over regions because the model accounts for crop environment interactions. An aspect that is gaining more interest is the use of models to set breeding goals. For example, simple physiological measurements for screening of varieties could be helpful in making the processes more efficient. The models are used here to define physiological attributes that contribute significantly to crop production in a given environment (Kropff and van Laar 1993).

Set research priority.

Since resources for research are limited, pre-assessment of the benefits of particular research is an important issue. Models can be very helpful at that stage. Before starting the research, the model can be used to determine the dynamics of growth limitations of a particular crop. Research effort can be focused on those limiting factors (de Wit and Penning de Vries 1985).

Decision support system

Once reliable model is developed, it can be used to produce rules and algorithms to assist the farmer in his decision-making processes such as when to irrigate crop, when and how much to apply fertilizer, and when and where to apply pesticide. In crop protection, simulation model is as indispensable tool in making decision to justify any action. Decision-making in crop protection management varies widely with different crops. Often, the use of pesticide plays a major role. Depending on the types of crops and diseases, treatments are applied when pest intensity reaches threshold, which justifies any intervention. Two of these kinds of examples are model that are used to predict economic threshold for Malayan black bugs and brown plant hopper infestations on rice (Mohd Norowi and Ahmad 1991; Mohd Norowi 2001)

Formulating policy

The output from crop simulation model can be used as input into other models to help the policy makers to formulate the best policy based on various available options (Rabbinge and Latesteijn 1992). One example of this kind of model is SYSNET (Roetter et al. 1998). The system is developed to optimize land used in Kedah-Perlis region under various projected scenarios. In the process, the outputs from various crop models were used to estimate yields that were integrated with various data on policy views and development plans into IMGLP (interactive multiple goal linear programming). The output from this system may combine with GIS to produce land use options and achievements.

CONCLUSIONS

The development of rice growth model has improved our understanding on some of the ecological processes that are crucial in our effort to increase rice production to enable us to feed the ever-increasing population in sustainable manner. The success of the development of this model is no doubt largely dependent on the capability to rely on mathematical models. In short, the values of mathematical model in sustainable agriculture development can been sees as below:

- as indispensable tool to increase our understanding of the crop growth and to provide direction in our research;
- as an aid for teaching and learning; and
- as a tool for management and decision-making

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TABLE 1: Summary of mathematical models use for calculation procedures of daily rice photosynthesis

Process	Mathematical models	Equation
Leaf photosynthesis for three canopy depth	$Y_L = Y_m(1\text{-exp}(-\varepsilon I_L/ Y_m)$ Y_L = the rate of gross photosynthesis Y_m = the rate of gross photosynthesis at light saturation ε = the initial light use efficiency I_L = the amount of absorbed radiation (PAR)	1
Profile of absorbed radiation in the canopy	$I_L = (1- \rho)I_0\text{exp}(-kL)$ I_L = the net PAR flux at depth L in the canopy I_0 = the flux of radiation at the top of canopy L = the cumulative leaf area index (counted from the top to the canopy downwards) ρ = the reflection coefficient of the canopy k = the extinction coefficient for PAR	2
Effect of environmental on photosynthesis (Y_m)		
Effect of ambient CO_2 concentration	$Y_x = Y_0(1+\beta\, ln\, (C_x/C_0))$ x = new CO_2 concentration 0 = normal CO_2 concentration (340 ppm) C = CO_2 concentration β = constant (0.8 for C3 plant)	3
Effect of leaf nitrogen content	$Y_N = -6.5 + 32.4\, N$ Y_N = the rate of gross photosynthesis at light saturation in response to N N = leaf nitrogen concentration	4

TABLE 2 :Result of the simple linear regression analysis and the partial *F*-test generated for quantification the goodness of fit of model prediction on various rice growth components (From Mohd Norowi 2001)

Variables	slope		*F*- ratio	*F*- probability.	% variance accounted for	*df*	partial *F* test	
	estimate	S.E.					*F*-ratio	*F*-probability[1]
Without BPH infestation								
Leaf area index (LAI)	1.037	0.049	95.58	<0.001	88.85	12	0.287	3.885
Weight of crop (WAG)	1.030	0.031	511.74	<0.001	97.71	12	0.473	3.885
Weight of panicle (WPA)	0.963	0.055	119.63	<0.001	96.76	4	0.221	6.944
Weight of stem (WST)	1.037	0.022	851.57	<0.001	98.61	12	1.457	3.885
Weight of green leaves (WLVG)	0.827	0.039	138.00	<0.001	92.00	12	9.774	3.885
Weight of dried leaves (WLVD)	0.924	0.056	68.95	<0.004	94.52	4	0.923	6.944

[1] Tabulated *F* at *P*=0.05, 2, degree of freedom of mean standard error of regression line.

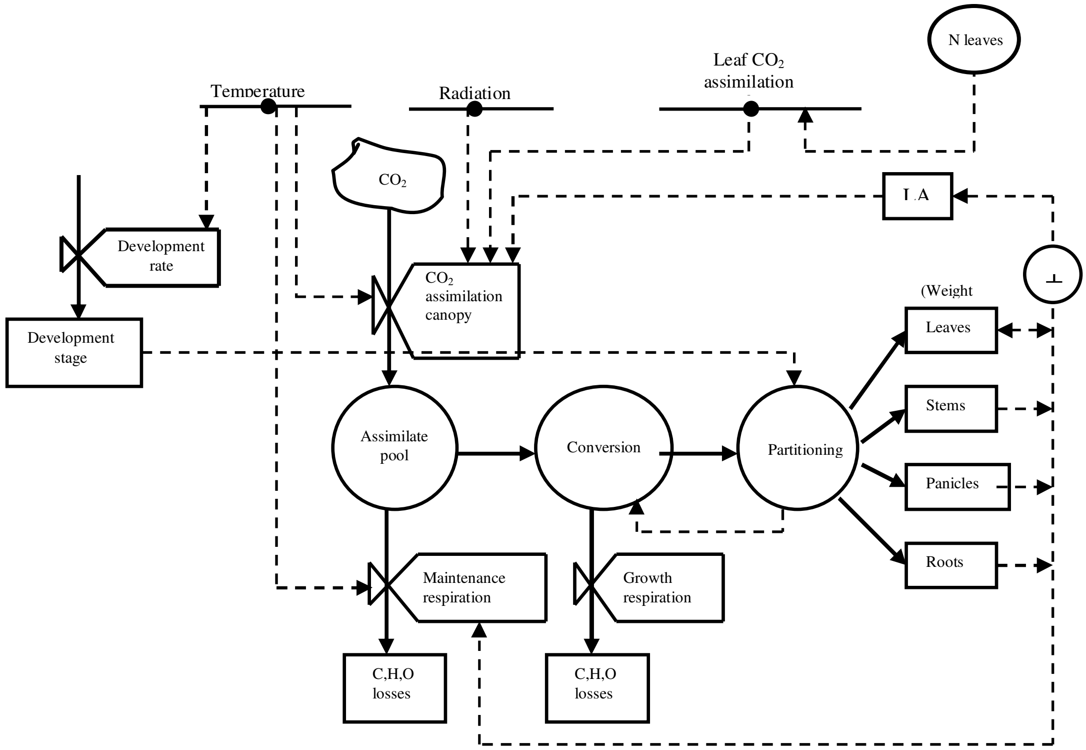

Figure 1: A schematic diagram illustrating the calculation procedures of rice growth model [Adapted from (Kropff et al. 1994)]