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Virtual Crop Root System Model Depending on Topological Structural and Biomass Available Partitioning

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Abstract: This study has developed a model for development and growth of root system based on the feedback mechanism among function and structure. Firstly, the basic structural Unit of Root (UR) was defined referring to the equal thermal interval. And then, the topological structures that characterized the number of URs and linking relationships among URs were simulated by dual scale automation. Based on the dynamics topological structure, the partitioning of the biomass available of root system from the plant was performed according to the sink and expanding rate of each UR. The parameters of the model were calculated or set by the literature data. Finally, we used the model to simulate the processes of development and growth for two kinds of typical root system including fibrous root system and taproot root system. The root model will provide a promising way to integrate the shoot system and root system of plant in the same time scale and formation details.

Key words: Visualization, structure, biomass partitioning, root system model

INTRODUCTION

Now more and more researchers are aware of the importance of the crop system model. It can integrated information from different crop subsystems to help us better understand the processes of responds of crop to environment and identity the limiting factors to crop growth and yields (Guo *et al*., 2006; El-Sharkawy, 2011).

In many plant model systems, the functional-structural plant models are a kind of promising models (Yan *et al*., 2004; Godin and Sinoquet, 2005). These models are based on the interaction of the plant's structure with the function and can be used to quantify processes of competition of obtaining resources in the plant as well as the competition with other plants and assess exploitation efficiency of soil resources etc. (Bidel *et al*., 2000; Bionsini, 2001). Now, the models have been successfully applied in the shoot system of plant (Allen *et al*., 2005; Renton *et al*., 2005; Guo *et al*., 2006). However, the relevant work of root system for functional-structural models has not obtained enough development because of complexity of root systems and the difficulties of observing and sampling them in the soil. And furthermore no obvious morphological marks which are used for discerning root growth unit (Zhang *et al*., 2006).

Up to now, many models for root system have been developed and have been applied to many aspects (Lynch *et al*., 1997; Pages *et al*., 2004). However, these root system models can not integrate with the shoot system in the same time scale and formation (Drouet and Pages, 2003). So most of the works about interactions among plants and environments can only considered the shoot system or the root system. These have limited our understanding of plant-environment system from the entire aspect. In order to integrate shoot parts and root parts of plant from an entire point, we will carry out the study that develops a root functional-structural model in an analogous way like the shoot model.

The objective of this study is to develop functional-structural model of root system based on the characteristics of root system and principle of plant model of Green Lab. and then, the processes of growth and development of two kinds of typical root system was simulated with the visual ways based on the parameters of the model from the literature data.

MODEL PRINCIPLE

Topological structure: For the shoot system, the organ development was relatively stable and the unit time was determined by the external morphology (Yan *et al*., 2004). For the root system, however, the time unit (T_0) for root development was set prior according to corresponding time unit of shoot model (Zhang *et al*., 2006). Based on

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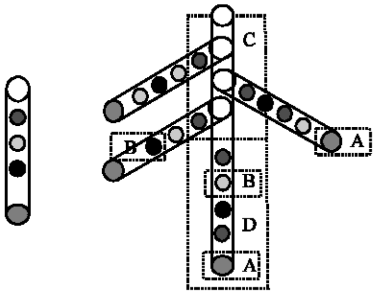

Fig. 1: The right panel was basic structural Unit of Root (UR). The left panel was entire root system consisting of different URs and A was for an apical meristem, B for lateral primordium, C for a UR, D for a new UR

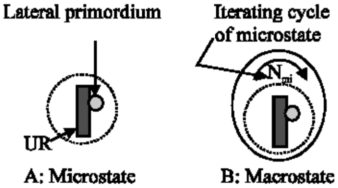

Fig. 2: Illustration of microstate and macrostate in the root dual-scale automaton

the T_0, the basic structural Unit of Root (UR) was defined as the root segment with the lateral primordium and root tip produced at the time interval of T_0 in the root system. Figure 1 illustrated the relationships about URs, lateral primordia, apical meristem and entire root system.

After definition of UR for root system, the dual-scale automaton was revised to describe the topological structure (Zhao *et al*., 2001; Zhang *et al*., 2006). The microstate was for UR and the macrostate consisting of a certain number of microstates served the root axis (Fig. 2). Based on the microstate and macrostate, the root topological structure was simulated by the combination of microstates and macrostates and transferring among different microstates and macrostates (Zhang *et al*., 2006).

Biomass partitioning: The principle of biomass partitioning used in this root model was from model of GreenLab (Yan *et al*., 2004). Each UR obtained biomass available according to the relative value of product of its sink and expanding rate. Considering the characteristics of root system, we assumed that expanding process of each UR was divided into two states. The first stage of expanding process of each UR was called axial expanding stage which was finished in one growth cycle. The UR competed for biomass available according to its axial sink strength. The second stage was called radial expanding processes and started after the first stage was finished and was finished in many cycles. The UR in each growth cycle of the second stage competed for biomass available referring to the product of its radial sink strength and its sink expanding rate which was the function of its growth age. Based on the above assumption and principle of GreenLab model, we could calculate the total biomass needed theoretically for all the URs in each growth cycle. If the biomass available in each GC was known, the value of produce of sink and expanding rate revised by the rate of biomass needed theoretically to biomass available was the actual biomass of each UR by axial expanding or radial expanding (Zhang *et al*., 2006).

Dynamic interaction between biomass partitioning and root structure: In the first GC, the topological structure was set, for example, there was one UR with RT 1 and GA 1 in the entire root system. The biomass that UR obtained was all biomass that root system provided. In the second GC, the length of UR which obtained biomass in the first GC was calculated by allometrical relationship between root length and biomass calculated by experimental data. The lateral primordium generated by UR was the product of length and branch density that was the lateral root number per unit length of UR. This method produced the topological structure of the second GC. Then using above methods describing the biomass partitioning, the biomass and accumulated biomass of each UR obtained in different GC were calculated dynamically.

Parameters for simulation growth and development of fibrous and tap root system: The main subject of parameterizing the model was to do some analysis on special scenarios, not did some exact prediction. The value of T_0 was set to 20°C, corresponding to one or two days. The total accumulated temperatures for maize root system growth is taken 2000°Cd (base temperature is 6°C above zero) and for cotton root system growth is 2600°C (base temperature is zero°C). The accumulated biomass in the nth GC was calculated by experimental data of Eq. 1:

$$Q_a(n)=\begin{cases} 1.65\cdot 10^{-2}\cdot n, n<11 \\ 1.10\cdot 10^{-9}\cdot n^6-3.15\cdot 10^{-7}\cdot n^5+ \\ 3.12\cdot 10^{-5}\cdot n^4-1.28\cdot 10^{-3}\cdot n^3+ \\ 2.44\cdot 10^{-2}\cdot n^2-1.55\cdot 10^{-1}\cdot n^1+ \\ 2.47\cdot 10^{-1}, n\geq 11 \end{cases} \tag{1}$$

where, Q_a (n) is the accumulated biomass of root system in nth GC.

For maize root system, the relevant parameters were listed in Table 1. The parameters of cotton root system were from the literature (Zhang *et al*., 2006).

Visualization and application: Using our virtual crop root system model with the parameters from Table 1 and relevant literatures, development and growth of root system of maize and cotton depending for its topological structure and biomass partitioning in the homogenous soil were simulated dynamically.

Table 1: Parameters of maize root system

Symbol	Meaning	Values
K	Max number of RT	10
i	RT of UR	1,2,3,4, 5,6,7,8,9,10
$N_{mi}(i)$	Iterating number of microstate	30, 28, 35, 40, 20, 28, 30, 10, 15, 20
$N_{ma}(i)$	Iterating number of macrostate	1, 1, 1, 1, 1, 1, 1, 1, 1, 1
$N_D(i)$	Delay GCs of microstate	6, 6, 10, 10, 4, 6, 8, 4, 6, 0
Bd(i)	Branching density	6, 6, 8, 10, 3, 4, 5, 1, 1, 2
sq(i)	Transferring macrostate after iterating	0, 0, 0, 0, 0, 0, 0, 0, 0, 0
Pa(i)	Sink of axial expanding	1, 0.8, 1.4, 2, 0.1, 0.2, 0.6, 0.01, 0.02, 0.1
$R_0(i)$	Diameters of axial expanding (mm)	20, 15, 24, 40, 6, 14, 20, 3, 8, 10,
Lw(i)	Ratio of length to weight(cm g^{-1})	30, 40, 30, 10, 250, 200, 100, 500,
G(i)	Factors of geotropism(degree)	400, 200, -0.2, -0.1, -0.1, -0.3, -0.05,-0.06,
$\alpha_b(i)$	Branching axial angle(degree)	-0.08,-0.01,-0.02,-0.03
$\beta_b(i)$	Branching radial angle(degree)	90, 90, 90, 90, 90, 90, 90, 90,
90,		
		9
$\alpha_g(i)$	Extending axial angel (degree)	0
$\beta_g(i)$	Extending radial angle (deg	(0~360)
		5, 5, 5, 5, 10, 10, 10, 20, 20, 20 (0~360)

Simulation of fibrous root system: When simulating the maize root system, initial seed root was firstly generated from seed. After several GCs, second seed roots were initiated from initial seed root. After more several GCs, the nodes root began to initiate from stems. And the initial seed root began to produce lateral roots with RT 5 after six GCs. Then, several growth cycles later, the roots with RT 5 begin to produce roots with RT 7.

According to such ways, the topological structure of maize root system maize was produced (Fig. 3, 4a, c and e). In each growth cycle, biomass available

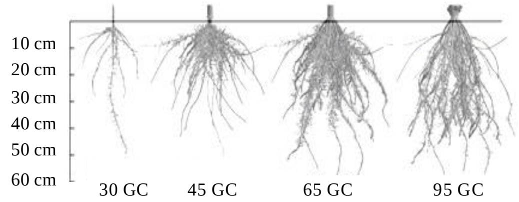

Fig. 3: Visual simulation of fibre root system of maize in the different growth cycles

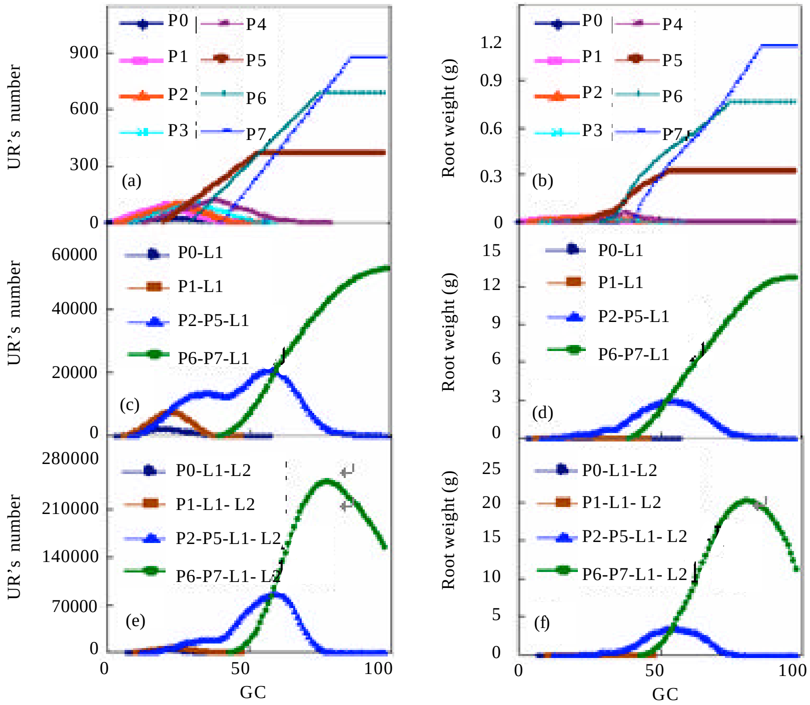

Fig. 4(a-f): Simulation of change for the number of URs (a, c and e), biomass partitioning (b, d and f) of URs for maize root system in different growth cycle. P was for node root, L1 for the first lateral root and L2 for the second lateral root

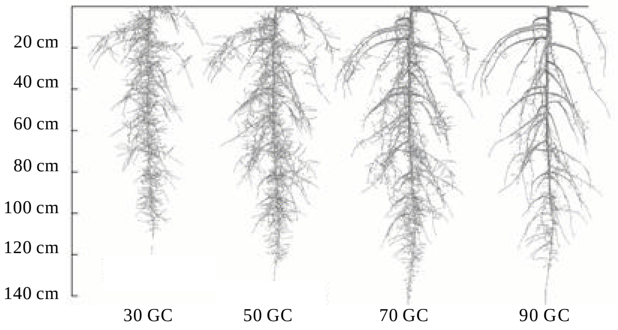

Fig. 5: Visual simulation of taproot root system of cotton in different growth cycles

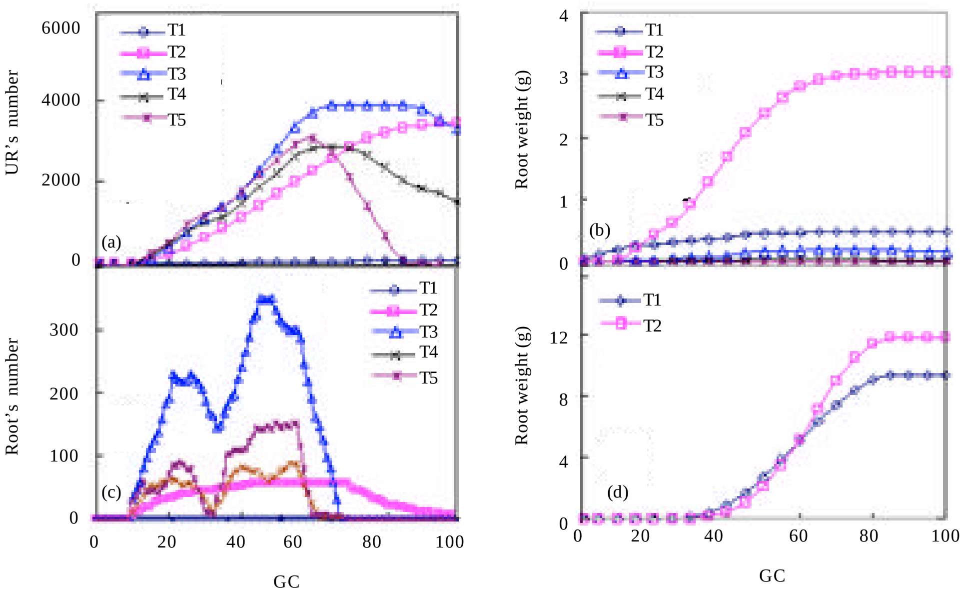

Fig. 6(a-d): Simulation of change for the number of URs, root individual number and biomass partitioning and accumulation of URs in cotton root system in different growth cycle. T1-T5 were for different root type

partitioning is finished. Figure 4b, d and f described the results of the processes of biomass partitioning in different URs in different Gcs.

Simulation of tap root system: When cotton root system began to grow, the taproot with RT 1 firstly expanded, several growth cycles later, different type roots with different RTs (URs with RT 2, or 3, or 4, or 5) were produced in the taproot from it base to apical according to its branch probability (Zhang *et al*., 2006). After several growth cycles, some lateral roots began to produce new lateral roots.

Figure 5 and 6a and b were the simulating results of the development and growth of cotton root system in different GCs. The biomass partitioning for UR in taproot root system like cotton included two steps. The first step was the axial expanding process, the results were showed in Fig. 6b. The second step was the radial expanding processes. Figure 6d showed the results by the radial expanding of UR to obtain biomass. In another aspect, the model can simulate the self-pruning of URs due to its ageing (Fig. 5).

CONCLUSION

The structure framework of functional-structural model of root system was developed. The simulating results showed that the root model can describe the dynamic processes of development and growth. The next work is to validate the model using the special experiments systematically.

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