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Abstract. Visualization study on the growth of virtual plant roots is of great significance to enhance the overall level of research on virtual plant growth. In this study, with the tobacco root as the object, its growth was divided by systematic analysis into three stages: root emergence, root growth, and root branching. Through the quantitative analysis of the morphological data of the tobacco root and in combination with results of previous studies, the tobacco root growth, branching and other models were established, and parameter values of the models were extracted. On this basis, computer graphics technology was applied to establish a virtual visualization system for tobacco root growth that should be capable of simulating root growth and computing indicators of roots including the number, length, density, etc. Results indicated that this system can do a better job of simulating the morphological features for the tobacco root and virtually displaying the process of tobacco root growth in a more realistic way.

Keywords: Tobacco, root, simulation model, virtual plant, visualization.

1 Introduction

With its rapid progress, the virtual plant study has become one of the frontier fields of research on agricultural sciences since the 1980s. Virtual studies have been successively carried out at home and abroad on corn, wheat, and rice [1-4]. The root is one of important integral organs. Diggle [5-6] established the first three-dimensional model of root age, location, and root segment orientation. Over 20 years of development, virtual root growth models of different plants were established through the L system, fractal method, reference axis technology, and method of three-dimensional reconstruction of plants [7-14]. However, these models have not taken the relationship between the root structure and its function into account. Simulation studies on roots have developed slowly because of the invisibility of the environment of root growth as well as the limitations in measurement techniques; the study on the

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tobacco root is even rarely reported. Tobacco is a special economic crop featured by the double-peak phenomenon in its root growth, which has a direct impact on the quality of tobacco. In this study, the experiment was designed with the rhizobox method to systematically investigate the morphological development of the tobacco root, and the model of tobacco root growth and development was established by summarizing previous results and analyzing test data of tobacco root morphogenesis. Based on the morphological model, a virtual growth system of the tobacco root was established with OpenGL in the Visual C + + platform. The visual expression of morphological characteristics in the process of tobacco root growth was initially realized, so as to provide a technological basis for virtual crop studies.

2 The Dynamic Model of Tobacco Root Growth

2.1 Root Emergence

The tobacco has a taproot system that consists of primary, lateral and adventitious roots. It is measured that the root begins to emerge when the effective accumulated temperature that is ≥10℃ in the seedbed period comes up to 100°C, and the total number of roots is in an exponential relationship with the accumulated soil temperature. It is also known that there is a linear relationship between the accumulated soil temperature at 5 cm below the ground and the accumulated gas temperature in seedbed period, thus the number model of roots in seedbed period is shown as follows:

$$N_0 = 0.3397e^{(0.9303T+14.547)} \quad (1)$$

T represents the accumulated gas temperature from seed-sowing to some day.

2.2 Root Growth Model

Root growth is represented by potential growth rate dP_{ri} / dt and actual growth rate dR_{wi} / dt that are under the influence of the soil temperature, the sunshine duration, and the carbohydrate supply from above the ground. The potential root growth rate[15] could be described by a kinetic equation:

$$\frac{dP_{ri}}{dt} = R_{ci} \bullet R_{wgi} \quad (2)$$

In Equation (2), i represents the sequence of soil layers; P_{ri} is the root's potential growth ($mg \bullet cm^{-3} \bullet d^{-1}$) in the i^{th} soil layer; R_{wgi} shows the root's dry weight ($mg \bullet cm^{-3}$) of the i^{th} layer; R_{ci} indicates the rate constant of root growth in the i^{th} layer which depends on the soil temperature and sunshine duration.

$$R_{ci} = D_L(R_K \bullet T_d - R_b) + (24 - D_L)(R_K \bullet T_n - R_b) \tag{3}$$

Where, D_L represents the available sunshine hours（h）; $R_b(1 \bullet d^{-2})$ is the soil constant; T_d and T_n represent the average temperature during the day and at night respectively, which could be obtained by the following formula:

$$\begin{cases} T_d = 0.55(T_{\max} - T_{\min}) + T_{\min} \\ T_n = 0.15(T_{\max} - T_{\min}) + T_{\min} \end{cases} \tag{4}$$

In Equation (4), $T_{\max}$ and $T_{\min}$ represent the maximum and minimum temperature in the soil, respectively. If CH is in abundant supply, the actual root growth rate is equivalent to the potential rate (dP_{ri} / dt); if the CH supply is insufficient, the actual root growth rate is calculated as follows:

$$\frac{dR_{wi}}{dt} = \frac{CH + CH_d}{\sum_i P_{ri}} \frac{dP_{ri}}{dt} \tag{5}$$

In Equation (5), CH_d is the part that is lacking in CH supply, i.e., the difference between CH required and CH actually provided. The actual CH supply to the root from above the ground within time Δt is shown as follows:

$$CH = f_{CH}(t) \bullet DMR \bullet \frac{\Delta DMA}{DM} \bullet \Delta t \tag{6}$$

In Equation (6), DM is the tobacco's amount of accumulated dry matter ($mg \bullet cm^{-2}$); DMR, the amount of accumulated dry matter within unit time Δt ($mg \bullet cm^{-2} \bullet d^{-1}$); ΔDMA, actual amount of dry matter growth within Δt; and $f_{CH}(t)$, the supply coefficient of the tobacco plant.

2.3 The Stretching Direction Model

Based on the model of root growth direction by Pages et al, environmental factors such as soil during root growth are set aside in this system. Under the hypothesis that the root grows in the homogeneous soil with the relatively superior growth environment and without serious environmental stress, the ultimate growth direction of the root within in current growth cycle depends on factors in three categories: the growth direction of the root in the previous cycle, geotropism, and random factors. Therefore, the stretching direction of new root tip D_N could be expressed as:

$$D_N = D_{N-1} + D_G + D_N' \tag{7}$$

Where, D_{N-1} is the growth direction of the root in the previous cycle, represented by the cosine function of the straight direction the root follows; D_G is the downward growth trend of the root, a vector pointing to the center of the earth; random factor D_N' is the deviation between the axial angle and the radial angle based on the original direction, represented by ϕ and θ whose value ranges from 0 to30^{o}and from -180^o to180^o, respectively.

2.4 The Root Branching Model

2.4.1 The Branching Locations of the Root

Because of apical dominance, lateral roots arise within a certain range on the mother root [16]. As shown in Figure 1a, the length of the non-lateral-root section at the lower part of the primary root was set as LB while that at the top part was LA, so lateral roots would only appear when the root axis was longer than the sum of LB and LA. Shown in Figure 1b, branching points B and C both occurred in root segment AD. The number of points similar to B and C determined the branching density of this root segment. Since B and C were assumed in the system to occur at any part on root segment AD, then if the coordinate of point D was known, then starting points B and C of the branching root axis could be determined with location coefficient

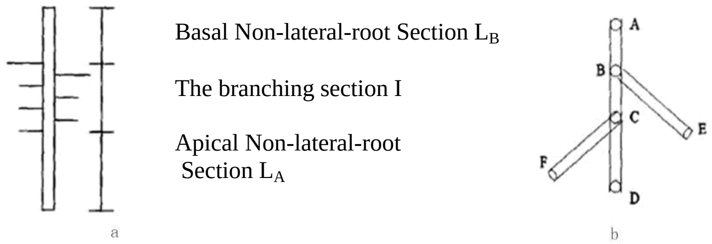

Fig. 1. Branching Locations of the Root Axis.

ε and the coordinates of A and D. ε, a random quantity in [0,1], is defined as:

$$\varepsilon = \frac{|AB|}{|BD|} \tag{8}$$

In this way, the starting point coordinate of the root axis growing from B, any point on root AD, is as follows:

$$\begin{aligned} x_B &= (\varepsilon \bullet x_D + x_A)/(1+\varepsilon) \\ y_B &= (\varepsilon \bullet y_D + y_A)/(1+\varepsilon) \\ z_B &= (\varepsilon \bullet z_D + z_A)/(1+\varepsilon) \end{aligned} \tag{9}$$

2.4.2 The Root Branching Directions

The branching direction of the root is jointly determined by the axial branching angle β and the radial branching angle α. The direction vector of mother root $\vec{u}$ would change into $\vec{u}'$ through the axial rotation of angle β, and the new vector would become vector $\vec{u}''$ by the radial rotation of angle α, i.e., the new branching direction. α and β range from 0 to180^{o} and from 0 to 90^{o}, respectively.

2.5 The Root Number and Length

The primary root grows rapidly after its emergence. When reaching a certain branching age, the primary root generates the primary lateral root, which produces the secondary lateral root at the branching age.

The number of primary lateral roots:

$$N_1 = \sum_{i=1}^{n} N_{1i} \tag{10}$$

where, number 1 represents primary lateral roots and i is their ordinal number.

The number of secondary lateral roots:

$$N_2 = \sum_{i=1}^{n} N_{2i} \tag{11}$$

in which number 2 represents secondary lateral roots and i is their ordinal number.

The total number of roots:

$$N = N_1 + N_2 \tag{12}$$

As regards to the root length, the lengths of all roots within the same level are calculated based on root levels. The formulas are as follows:

The length of primary lateral roots:

$$SL_1 = \sum_{i=1}^{n} SL_{1i} \tag{13}$$

The length of secondary lateral roots:

$$SL_2 = \sum_{i=1}^{n} SL_{2i} \tag{14}$$

Total root length:

$$SL = SL_1 + SL_2 \tag{15}$$

The length of root segment is calculated as follows:

$$sl = \frac{|z_2 - z_1|}{\sin\left(arctg(\frac{|z_2 - z_1|}{|y_2 - y_1|} \bullet \sin(arctg(\frac{|y_2 - y_1|}{|x_2 - x_1|}))) \right)} \qquad \textbf{(16)}$$

Where, x_1, y_1, z_1 and x_2, y_2, z_2 represent the coordinates of starting and ending points (points A and B of the root segment) respectively.

2.6 Determination of Model Parameters

The development of the tobacco root is under the influence of a number of factors, such as soil moisture, ground temperature, carbohydrate supply, dry matter accumulation, and its own characteristics. According to experiments and related literature [17] parameters that affect models of tobacco root growth and branching are shown in table 1.

Table 1. Parameters of root growth and branch models.

module	Parameter	Value	Unit
Model of root growth	Soil parameter Rk	0.0125	$1 \cdot d^{-1} \cdot ℃^{-1}$
	Soil parameter Rb	0.125	$1 \cdot d^{-2}$
	Support ratio of tobacco fCH(t)	0.15	
	Root weight in the ith soil layer Rwgi	Rwgi=0.765/(1+exp(17.734-0.152t)) When i=0-10cm t≥80d Rwgi=0.495/(1+exp(10.146-0.088t)) When i=10-20cm t≥80d Rwgi=0.275/(1+exp(9.317-0.079t)) When i=20-30cm t≥80d Rwgi=0.136/(1+exp(11.589-0.094t)) When i=30-40cm t≥95d	$mg \cdot cm^{-3}$
Model of root branch	Length of non branch on basis of main root LB	0.5	cm
	Length of non branch on top of main root LA	2	cm
	Length non branch on basis of first order root L1B	1	cm
	Length non branch on top of first order root L1A	5	cm
	Branch age of main root age0	3	d
	Length between branches on main root length0	0.1	cm
	Branch age of first order root age1	7	cm
	Length between branch on first order root length1	0.1	cm

3 Three-dimensional Simulation of Tobacco Roots

3.1 Design Methods

Tobacco roots are considered as a group of branch axes, that is, the primary branch (primary lateral root) is connected to the primary root, and the secondary branch (secondary lateral root) is connected to the primary branch, etc. Everyday, there might be new branch axes, and the existing root axes might grow and branch. To determine the spatial location of roots, it is necessary to know enough spatial coordinates of points on roots. Suppose that root axis is composed of a series of linear root segments in different directions, since the root segments are developed from growing apexes' moving to the new locations in a limited period of time, two coordinates are enough to determine its spatial location.

During the simulation, the accumulated temperature cycle of root growth 1d is set as one step. Within each time step, all the survival root segments in each growth cycle are first updated, (three-dimensional correlation connections of root segments, branch levels, spatial coordinates, geometric sizes, branching sequences, etc.), according to the models of root growth and branching, and all the updated information serves as the basis of root parameters (root length, number, root length index, root length density, etc.) calculation. Then, based on the rule of mass distribution, the mass quality distributed to individual roots is obtained, and the potential demands of new roots' absorption are calculated based on soil resistance and temperature of the surrounding soil of the root segments. If the quantity available for absorption assigned to the roots is less than the potential requirements, then all the root segments would shrink back accordingly. Root simulation flow-process is shown in Figure 2.

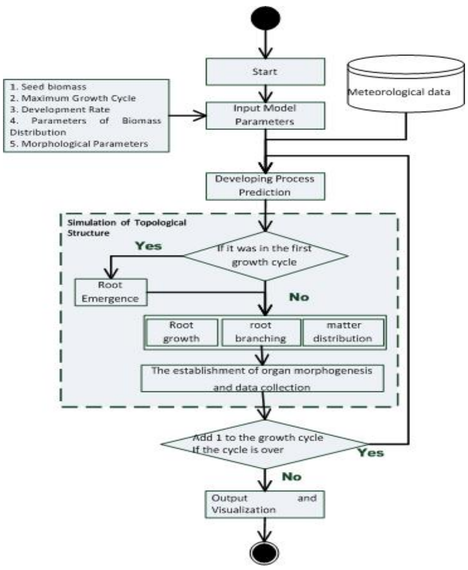

Fig. 2. Flow of Simulation of Tobacco Root Growth.

3.2 Data Structure

Plant roots had a clear hierarchical relationship, which can be described with the tree structure. Each root is decomposed into multiple nodes, with each node representing a root segment. Stored in the form of structural element, the node carries the required information for root growth. The running program visits and links each node in the tree structure, thus the morphological structure of the root is obtained. The data structure is shown as follows:

```
struct rootdata    // The data structure to store the root data
{
      float  x1,y1,z1;  // To store the starting point of root segment
      float  x2,y2,z2;  // To store the ending point of root segment
      int phy_age;      // To store the physiological age of root segment
      int growth_age;          // To store the growth age of root segment
      struct rootdata *next;  // The pointer pointing to the next data in
                                 the linked list
      struct rootdata *pre;   // The pointer pointing to the pervious data
                                 in the linked list
      struct rootdata *f;     // The pointer pointing its father node
  }
```

Information contained in this data structure is: (1) the spatial coordinates of the endpoint of the root segment, with which the direction of root growth is determined; (2) the physiological age of the root, one of the root properties, through which the physiological age of the root or the root segment, parameters about the geometrical size of the root, branching conditions, the factor of geotropism during growth, and parameters of axial angles are correspondingly identified to determine the behavioral characteristics of the root; (3) the growth age of the root, reflecting the number of cycles the root axis has experienced since its emergence from the mother axis, which was primarily used to characterize that roots of the same physiological age have the same growth rate at different ages of growth; (4) data pointers, which are used to establish logical relations among data.

3.3 Data Structure

It is supposed that the root begin to grow at point (0, 0, 0), and the root growing out of the origin point is a primary root. In the general sense, if it is supposed that the current root is at level N; A is the starting point of the root; and D is the ending point, then another root growing out from this root (within the line segment BC) is in level N+1, and the root emerging at point B is in level N. With Figure 3b, the root information is determined as follows:

(1) The first root A1

$$A_1 \to x_1 = 0, A_1 \to y_1 = 0, A_1 \to z_1 = 0$$
$$A_1 \to x_2 = 0, A_1 \to y_2 = 0, A_1 \to z_2 = 0$$
$$A_1 \to age = 1, A_1 \to rank = 1, A_1 = radius = R_{\min}$$

(2) For roots of lower order, B2 and C2, in accordance with the aforementioned branching model, ε_{C2} and ε_{B2} are randomly generated, which, coupled with the range of radial angle α and axial angle β, randomly generate (α_{B2}, β_{B2}) and (α_{C2}, β_{C2}). Therefore, the branch location and direction of branching root B2 are:

$$B_2 \to x_1 = A1 \to x_1 \cdot \varepsilon_{B2} + A1 \to x_2 \cdot (1 - \varepsilon_{B2})$$
$$B_2 \to y_1 = A1 \to y_1 \cdot \varepsilon_{B2} + A1 \to y_2 \cdot (1 - \varepsilon_{B2})$$
$$B_2 \to z_1 = A1 \to z_1 \cdot \varepsilon_{B2} + A1 \to z_2 \cdot (1 - \varepsilon_{B2})$$
$$B_2 \to age = 2, B_2 \to rank = 2, B_2 \to radius = R_{\min}$$
$$B_2 \to x_2 = B_2 \to x_1 + \nu_2 \cdot \cos(\alpha_{B_2})$$
$$B_2 \to y_2 = B_2 \to y_1 + \nu_2 \cdot \cos(\beta_{B_2})$$
$$B_2 \to z_2 = B_2 \to z_1 + \nu_2 \cdot \cos(\gamma_{B_2})$$

Those of branching root C2 can be determined likewise.

(3) For root of the same level (root tip), D1, in accordance with the aforementioned root extension model, ϕ and θ are randomly generated, that is, the random rotation of A1 in the axial and radial direction.

$$D_1 \to x_1 = A1 \to x_2, D_1 \to y_1 = A1 \to y_2, D_1 \to z_1 = A1 \to z_2$$
$$D_1 \to age = 2, D_1 \to rank = 1, D_1 \to radius = R_{\min}$$
$$D_1 \to z_2 = D_1 \to z_1 + \nu_1 \cdot \cos(\theta)$$
$$D_1 \to x_2 = \nu_1 \cdot \cos(\theta) \cdot \cos(\phi)$$
$$D_1 \to y_2 = \nu_1 \cdot \cos(\theta) \cdot \sin(\phi)$$

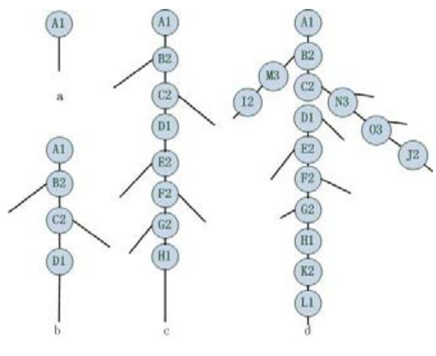

Fig. 3. Branching of Root Axis.

4 System Implementation

Based on the model of tobacco root development, the virtual system of tobacco root growth was established with OpenGL in the Visual C + + platform. Functions of the system mainly include: (1) the input of environmental parameters of root growth; (2) with the input parameters (sowing depth, soil constants, branching age, soil hydraulic conductivity, morphological parameters, biomass allocation, etc.) and meteorological data (sunshine duration, soil temperature, atmospheric density, atmospheric pressure, temperature, etc.), the system can output parameters about tobacco root growth at different stages (root length, root number, root length index, root length density, surface area, volume and water absorption as well as dry matter distribution, etc.) and three-dimensional visual results, allowing the examination of growth and distribution of tobacco roots from all angles. Figure 4a is the input interface of model parameters. Figure 4b, 4c and 4d are the visualization results of the tobacco root sown 80, 100, and 110 days respectively.

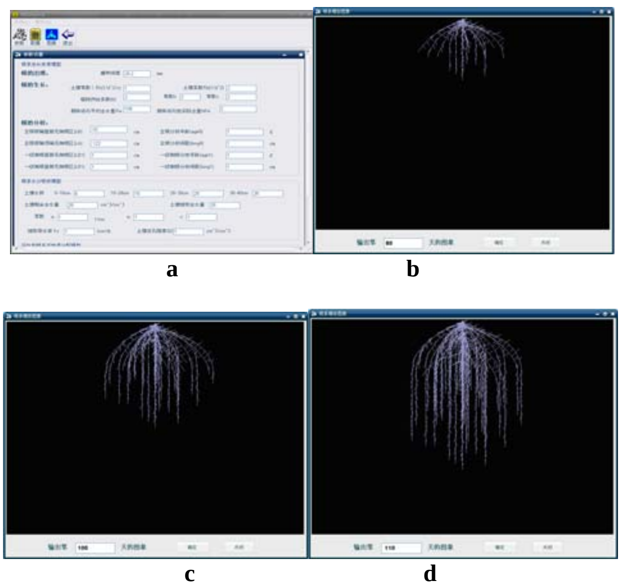

Fig. 4. Visualization of tobacco root growth.

5 Conclusion

Based on observations and studies of the structure, growth and distribution of the tobacco root morphogenesis, as well as the results of previous studies, the method of systematic analysis was employed to divide the growth of tobacco root into three stages: root emergence, root growth, and root branching. According to the quantitative relationship between tobacco root development and the environment, the growth pattern of each stage and the correlation between different stages were elaborated. Based on these patterns, a virtual system of tobacco root growth was created with computer graphics. The system is able to simulate the three-dimensional dynamic growth of the root and calculate the root parameters at the same time. The result suggests:

(1) Since the relationships between tobacco root growth and the environment, nutrition supply of aerial parts and root growth, etc. are considered systematically, the model is systematic and universal.

(2) The simulation result is basically consistent with the growth and development of tobacco root, and reflects the pattern of tobacco root growth and development. Thus, the system could be utilized as a tool to study the growth and development of the tobacco root, and assist the digitalized regulation for high yield and quality of the tobacco.

(3) In the simulation, the information of root development quantity, length, distribution characteristics at any given time is stored in the root description file. The content recorded in this file is not only the current output, but also the input information for subsequent simulations, thus making it possible to continue the previously aborted simulation. Therefore, it is ideal to study the impact of different environmental backgrounds on the morphology of a partially developed root with this function.

(4) Although the model rather successfully simulates the dynamic change of root morphological characteristics, it still needs improvement in terms of simulating the impact of local soil's nutrition distribution on the roots as well as the interactions and competitions between adjacent roots.

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References

1. Penning de Vries F W T, Jamsen D M, Ten Berge H F M, Bakerma A.: Simulation of ecophysiological processes of growth of several annuals crops. Netherlands: Pudoc. Wageningen(1989)
2. Liu Xiuhai, Xiao Boxiang, Zheng Wengang, Wang Danhong, and Yang Guanghui.: Survey on Virtual Growth and Development of Maize, Journal of Maize Science, China, 14(2),pp.164-167(2006)
3. Feng Liping, Gao Liangzhi, Jin Zhiqing, Ma Xinming.: Studies on the Simulation Model for Wheat Phenology, ACTA AGRONOMICA SINICA, China, 1997, 23, pp. 418-424.
4. Liu Hui, Tang Liang, Zhang Wenyu, Wu Yanlian, Cao Weixin, Zhu Yan.: Construction and implementation of model-based visual growth system, Transactions of the CSAE, China, 25(9), pp. 148-154(2009)

5. Diggle A.J.: ROOTMAP:A model in three-dimensional coordinates of the growth and structure of fibrous root systems, Plant and Soil, 105, pp.169-178(1998)
6. Diggle, A.J.: ROOTMAP: A ROOT GROWTH MODEL, Mathematics and Computers in Simulation, 30, pp.175-180(1987)
7. Adiku S.G.K. , Braddock R.D., Rose C.W.: Simulating root growth dynamics, Environmental Software, 11(1-3),pp.99-103(1996)
8. Pages L, Jordan M O, Picard D.: A simulation model of the three-dimensional architecture of the maize root system, Plant and Soil, 119, pp. 147-154(1989)
9. Wang Gongming, Guo Xinyu, Zhao Chunjiang, Yang Baozhu, Dong Zhengjie.: Analysis and Compare of Virtual Plant Roots Growth Model, Crop Research, 3,pp. 281-285(2006)
10. Ge, Zhenyang, Yan, Xiaolong, Luo, Xiwen.: Simulation models of plant root system architecture and application: A review, Transactions of the CSAE, 18(3), pp.154(2003)
11. Zheng Xuyang, Zhou Shuqiu, Guo Xinyu, Zhao Chunjiang, Wang Jihua.: Study on the Geometry Modeling for Corn Root System, Journal of engineering graphics, China, 4, pp.62-66(2004)
12. Feng bin, Yang Peiling.: Simulation of the Root Growth by Using the Image and Fractal Growth Technology, Journal of China Agricultural University, China, 5, pp. 96-99(2000)
13. Zhang Wuping, Li Baoguo.: Three-dimensional Model Simulating Development and Growth of Cotton Root System, Journal of System Simulation, 18(Suppl.1), pp.283-286(2006)
14. Kim Jijoon.: A growth model for root systems of virtual plants with soil and moisture control, IEICE Transactions on Information and Systems, E89-D(5), pp. 1743-1750(2006)
15. Bar-Yosef B, Lambert J R, Baker D N.: Rhizos: a simulation of root growth and soil processes, sensitivity analysis and validation for cotton, Transactions of the ASAE, 25: 1268-1273(1982)
16. Lungley D R.: The growth of root systems: A numerical computer simulation model, Plant and Soil, 38, pp.145-159(1973)
17. Feng S Y, Bar-Yosef B.: Simulation of long term nitrogen behavior in agricultural soil, Report on Cooperative Project, Carried out at Inst. of Soils and Water, ARO, Israeli. The International Cooperation Center, Ministry of Foreign Affairs, State of Israeli(1995)