SIMULATION OF FOREST EVOLUTION

Effects of Environmental Factors to Trees Growth

Jing Fan[1], Xiao-yong Sun [1,2]

[1] *The Lab of Software Development Environment, Zhejiang University of Technology, Hangzhou 310014, China*

[2] *School of Information and Electronic Engineering, Zhejiang University of Science and Technology Hangzhou 310014, China*

Ying Tang, Tian-yang Dong

The Lab of Software Development Environment, Zhejiang University of Technology, Hangzhou 310014, China

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Abstract: Out of the complexity and variety of plant communities, it is a challenging task to simulate the structure and dynamics of plant communities. In this paper we simulate and visualize the evolution of forests by the tree growth model influenced by the environmental factors. The environmental factors we considered include illumination, terrains and resource competition among trees. We develop our tree growth model based on the forest gap model by effectively incorporating the above environmental factors. The system is implemented with Visual C++ 6.0 and OpenGL. We compare the growth of trees (their heights and DBHs) which are of different ages or located in different regions. We also show changes of trees distribution within certain landscape for a long period of time (more than two hundred years). The illuminating and interesting experimental results show that our simulation technique is effective.

1 INTRODUCTION

Realistic simulation of ecosystems is a challenging topic, which involves bio-physics, ecology and human aspects. We define the distributions of plants across a plant community for a large period of time as the space-time distribution model of the plant community. This model determines the evolution of the whole plant community. In our study, we focus on the forest composed by several hundred trees. But only one kind of tree is discussed in this paper. More species of trees would be considered in the future study. We need to consider the interactions of trees with each other as well as the interactions with their environment to determine the space-time distribution model of the whole forest.

In this paper, we extend the method discussed by Sang Weiguo and Li Jingwen (Sang and Li, 1998) to develop our space-time distribution model. Our model incorporates the terrain as the influence factor which has not been considered in previous models. Actually, we adopt a two-level model, where the higher-level model determines the distribution of trees (their numbers and locations) in macro scale, and lower-level model determines the tree specific parameters (heights and DBHs) in micro scale.

The structure of the paper is arranged as follows. In the next section we briefly review previous related work on this topic. Section 3 introduces architecture of the system. In section 4 we describe the detailed specific models and implementation techniques. The simulation results are shown in section 5. Section 6 gives the final conclusion.

2 PREVIOUS WORK

Modelling and visualization of ecosystem is a difficult subject, mainly because of the complex interactions at various time and space. To simulate the distribution of plant community, University of Calgary extended the L-system and introduced Multiset L-system (Lane and Prusinkiewicz, 2002). L-system can be used to model the individual plant (Prusinkiewicz *et al.*, 2001). An L-system model

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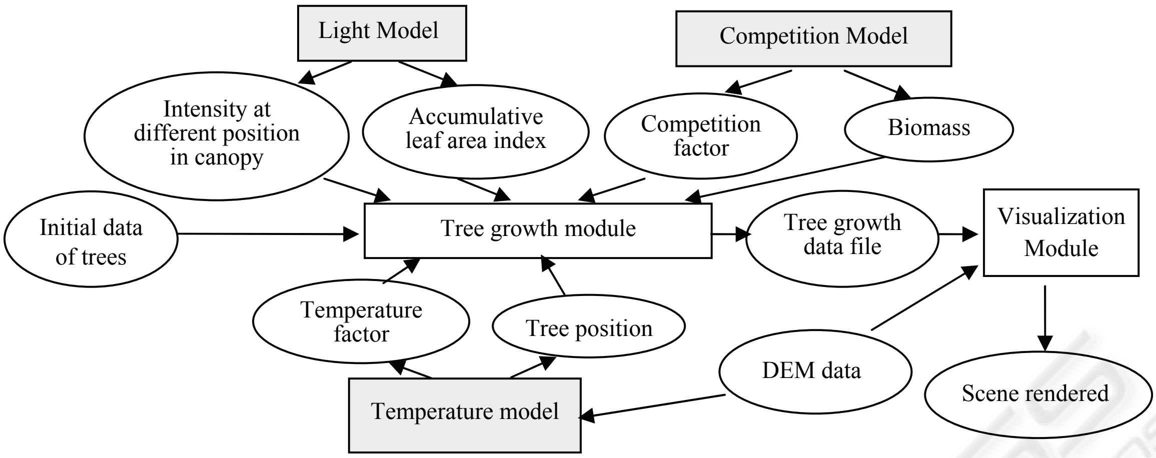

Figure 1: Forest evolving simulation system.

generates plants represented as strings of symbols with optional parameters (Prusinkiewicz and Lindenmayer, 1990). In Multiset L-system, the set of productions operates on a multiset of strings that represent many plants, rather than a single string that represents an individual plant. New strings can be dynamically added to or removed from this multiset, representing organisms that are added to or removed from the population. Based on Multiset L-system, Lane *et al.* (Lane and Prusinkiewicz, 2002) proposed a spatial distribution model of plants with the ecologically and visually important phenomena of clustering and succession of plants. The shortcomings of this approach are mainly the lack of retro-action between elements of the environment, as well as unrealistic dynamics.

GreenLab model which is based on Source-Sink Model and plant automation has been used in many plant simulation applications. It is a functional-structural model, which means that it combines both functional growth and structure development, interacting together (De Reffye and Hu, 2003). But currently GreenLab model is mainly applied to agriculture, and the research of applications in forestry is still in the very early stage. There are a lot of problems to be solved.

Forest gap model is one of the most active areas in research of forest ecology. It is a forest evolving model (Sang *et al.*, 1999). In forest gap model regeneration, mortality and growth of trees are influenced by their neighbors. In our system the forest gap model is extended with the terrain. We implement the system with Visual C++ 6.0 and OpenGL, and the result is satisfying.

3 SYSTEM ARCHITECTURE

In order to make our system scalable, it is designed to consist of three modules: tree growth module, environment module and visualization module. And the environment module includes temperature model, light model and competition model. The whole system architecture is shown in Figure 1.

3.1 Tree Growth Module

This module mainly includes the tree growth equations. The basic idea is that we first establish the tree growth function for the ideal state and later modify it by considering environmental factors. The values, which reflect the effects of different environment factors on tree growth, are to be computed in following environment module. Such computed values are mapped into the ideal growth function to get the actual growth of each tree. We establish a tree growth influence function for each kind of resource, the function will return a value in [0, 1] based on the resource condition. If the value equals 1, it means the resource is in its ideal state. If the value equals 0, it means trees can not survive in such environment. If the resource is inadequate or too much, the value is a positive number less than 1, then the tree growth will slow down.

In this module we only focus on the increase of tree's height and diameter at breast height (DBH), the topological structure of tree will be ignored. Such simplification speeds up the computation greatly, yet it also provides enough information for illuminating visualization.

3.2 Environment Module

Usually, the resource is not distributed uniformly across the forest. As we all know, temperature changes with height, slope direction will affect the amount of light, so the resource distribution needs to be modelled based on terrain.

In our system, the environment module includes temperature model, light model and competition model (Figure 1). As we have explained before, in the tree growth module each environment factor is represented by a value in [0, 1] which is computed in the environment module. The process to compute such coefficients is independent of the tree growth model, which makes the environment module scalable. If a new resource factor is introduced, the tree growth module needs not to be modified. What we need to do is just to add this resource to the environment module to get the value that is to be mapped into the tree grow function.

3.3 Visualization Module

Tree growth data including height and DBH are computed in tree growth module. These growth data, together with other tree information such as position, age of trees and so on, are written into a binary file as the input of visualization module. Visualization module renders the terrain scene with digital elevation map (DEM), and visualizes the trees' distribution based on the input data.

4 SPACE-TIME DISTRIBUTION MODEL OF FOREST AND ITS IMPLEMENTATION

In our system we extend the forest gap model to establish a space-time distribution model of forest including the tree growth model and the environment model.

4.1 Tree Growth Model

In this model growth, maturation and regeneration of trees must be taken in account, so the sub models are shown as follow.

4.1.1 Regeneration Model

If the regeneration takes place, number of regeneration is determined by (Sang and Li, 1998):

$$\mathrm{P}(n) = \frac{\lambda^n e^{-\lambda}}{n!} \tag{1}$$

where λ is the Poisson distribution parameter which represent the average number of tree regeneration, n is the number of tree regeneration, P(n) is the probability of regeneration number being n.

4.1.2 Mortality Model

The change in number and distribution of trees in forest is the result of regeneration and mortality which are carrying on at the same time. The mortality of the trees which grow normally is computed by (Sang and Li, 1998):

$$M_0 = 1 - (1-\varepsilon)^n \tag{2}$$

where n is the age of a tree, M_0 is the mortality of a tree at the age of n, ε is the annual mortality rate.

4.1.3 Growth Model

The tree growth equation in ideal state is given below (Sang and Li, 1998):

$$\frac{d(D^2H)}{dt} = \int_B^H S_L[\gamma P(z) - \delta z]dz \tag{3}$$

where D is DBH, H is tree Height, B is the clear bole height, z is the length from treetop to a certain position of the tree, P(z) is light reaction function, S_L is linear density of leaf area in crown canopy.

If the environment factors are taken into account, the equation can be modified as below:

$$\frac{d(D^2H)}{dt} = \mathrm{f}(T)_i * CE * \int_B^H S_L[\gamma P(z) - \delta z]dz \tag{4}$$

where $\mathrm{f}(T)_i$ is temperature factor, CE is the competition factor.

D^2H is volume index which reflect tree grow speed. If the volume index is computed, the height and DBH can be gotten based on the following equation (Sang and Li, 1998):

$$H = 1.3 + (H_{\max} - 1.3)[1 - \exp(\frac{SD}{H_{\max} - 1.3})] \tag{5}$$

whre $H_{\max}$ is the maximum tree height, S is a constant.

4.2 Environment Model

4.2.1 Light Model

Light will attenuate while transmitting through the forest canopy and the process obeys Lambert-Beer's Law (Sang and Li, 1998):

$$\mathrm{I}(z) = I(0)e^{-kL(z)} \tag{6}$$

where I(z) is the intensity at the position of z in forest canopy and light reaction function in equation (3) can be calculated based on I(z), k is the Extinction coefficient of the forest community, I(0) is the intensity right above the forest canopy, L(z) is the accumulative leaf area index of all trees in forest above position z.

4.2.2 Temperature Model

The influence of temperature on tree growth is measured by accumulated temperature. Accumulated temperature is an energy index that a plant completes its development cycle. It can be get by practical observation or calculated by the calculation formula proposed by Botkin. And then the temperature regulatory factor can be gotten (Sang *et al.*, 1999):

$$\mathrm{f}(T)_i = \max(0, TDEGD_i) \tag{7}$$

$$TDEGD_{\mathrm{i}} = \frac{4(gdd_{\max} - gdd)(gdd - gdd_{\min})}{(gdd_{\max} - gdd_{\min})^2} \tag{8}$$

where *gdd* is the effective accumulated temperature which can be get by practical observation, $gdd_{\max}$ and $gdd_{\min}$ are the maximum and minimum accumulated temperature of the tree species.

For the complexity of the terrain in forest, heights at different positions are significantly different. As temperature will change with height, so the tree growth rate at different height won't be the same. To simulate this phenomenon we introduce a DEM file to record the height at different position in forest, and then calculate the effective accumulated temperature based on the relationship between height and temperature. For biological zero for all trees of one species is the same, the change in effective accumulated temperature can be calculated as follow:

$$\Delta \mathrm{gdd} = \Delta \mathrm{T} * \mathrm{N} = f(\Delta H) * N \tag{9}$$

where $\Delta \mathrm{T}$ is the value changing in temperature which is a function of the height changed, ΔH is the value changed in height, N is the tree growing days in one year.

4.2.3 Competition Model

With the increment in the forest density and tree volume, the resource each tree can get become more and more less, then the tree growth will be inhibited. In our system, resources that have been occupied by trees are represented by actual biomass in forest, and environmental carrying capacity is represented by the max biomass in forest, then the competition effect function is shown as below (Sang *et al.*, 1999):

$$CE = 1 - \frac{W_{tot}}{W_{\max}} \tag{10}$$

where *CE* is the competition factor, W_{tot} is the actual biomass and $W_{\max}$ is the maximum biomass in forest.

Trees nearby to each other will not only compete for the resources in forest, but also reduce the light that trees nearby can obtain. This will lead to weakened photosynthesis of the trees, and then their growing rate will decrease. It cannot be ignored while modelling. So for calculating the competition effect factor, we need to determine the distance between trees, and then calculate the biomass and the influence to photosynthesis of the trees. As there are enormous numbers of trees in forest, it will be too computationally intensive that finding neighbors of a tree procedurally. So the neighbours' information needs to be recorded to increase execution speed.

Because of tree regeneration and mortality, the number of trees in forest is always in change, so we need a linked list to record the trees in forest. Each node in the linked list represents a tree. And the neighbors of a tree also need to be recorded by a linked list. So the data structure is a double linked list.

In the linked list pFirst is a pointer pointing to the first tree, pNext is pointing to the next tree in forest. Neighbors of a tree are also organized by a linked list which is pointed by a neighbors' pointer. Pseudo code of forest evolving is shown as below:

```
void Forest::evolve(){
   Tree * ps;
   //judge a tree will die or not
   for(ps=pFirst;ps;){
     if(ps->die()){
       Tree::deleteNeighber(ps);
       //delete ps in neighbor linked
            //list of other trees
       deleteTree(ps);
       //delete the tree pointed by ps
     }
     else{
```

```
            ps=ps->pNext;
            //judge the next tree
          }
        }
        // alive trees continue growing
        for(ps=pFirst;ps;ps=ps->pNext ){
              ps->grow();
        }
        //tree regeneration
        int newTree=numOfNewTree();
        for(i=0;i<newTree;i++){
              addTree();
        }
    }
```

In our system the evolving cycle is one year, so every year during the forest evolving process, function evolve() will be called to determine the condition of tree regeneration, growth and mortality.

5 SIMULATION RESULTS

In our system we take Korean pine (Pinus koraiensis) as example and suppose the forest is Xiaoxinganling, the mountain region of north-eastern China. Sang Weiguo and Li Jingwen (Sang and Li, 1998) have provided the related parameters of tree species and forest.

5.1 Growth Simulation of Single Tree

5.1.1 Ignore the Height Influence

According to the literature, at the age of 10, the height of Korean pine can reach 4.2 m, DBH is about 2.7 cm. At the age of 20, the tree height can reach 8.6 m, DBH is about 11.9 cm. At the age of 26, the tree height can reach 10 m, DBH is about 15.5 cm. In this experiment growth of single Korean pine is simulated in 100 years. As the DBH can be calculated by its height based on equation (5), in Figure 2 we only show the relationship between age of the tree and its height. Curve A shows the growing process of the tree at height of 0m where the temperature is supposed to be in ideal state for convenience. As shown in the figure, the result of our program is close to the actual growing progress.

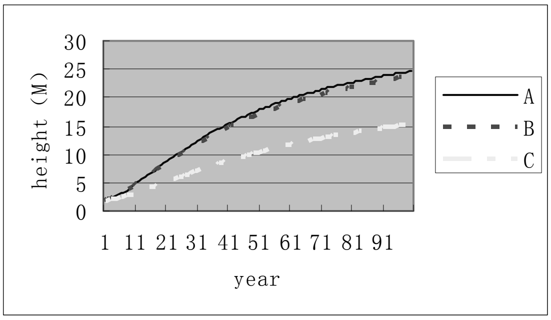

Figure 2: Relationship between age of the tree and its height.

5.1.2 The Influence of Height to Tree Growth

As in our system the height of 0m is set to be the optimal position on temperature, so when the height increases, the temperature decreases, then the tree growth will be inhibited. In Figure 2 curve B and C represent the tree growing process at the height of 100m and 300m separately. The curves show the influence of height (or temperature) to tree growth.

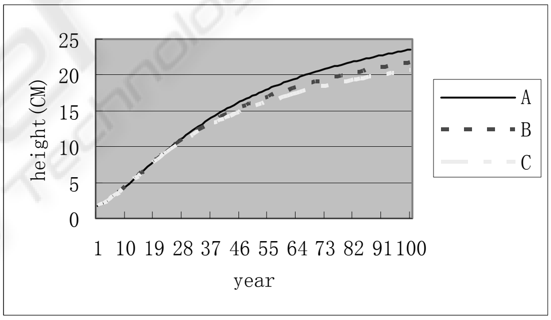

Figure 3: Growth of trees with different number of neighbours.

5.2 Growth Simulation of Multiple Trees

In this experiment there are 100 trees in the forest at different positions. As trees will compete for the limited resource, so the tree growth will be inhibited. The more neighbors a tree has, the bigger influence there will be to the tree growing process. In this experiment tree regeneration and mortality are ignored.

We chose three representative trees. In Figure 3, curve A represent a tree has one neighbor, B has three neighbors and C has five neighbors. As shown in Figure 3, the influence of neighbors to the tree growth will be bigger if it has more neighbors.

5.3 Tree Regeneration and Mortality Taken into Consideration

As the tree growth rate, mortality, the number of regeneration and their positions are random, every evolve result is different, we just show one of these.

5.3.1 Proportion between Different Ages

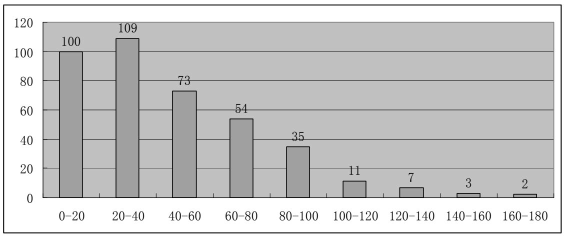

Figure 4: Proportion between different ages.

The number of trees in forest is set to 50 initially and it changes with trees regeneration and mortality. The number of trees increases significantly at the beginning, after a number of years evolving it tends to be stable around 400. When the program terminated there're 394 trees in the forest. Tree numbers of every 20 years is shown in Figure 4. Most trees are under age of 80 and few are over 100.

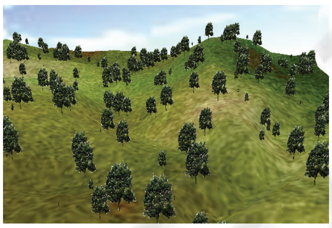

Figure 5: Scene rendered at the age of 50.

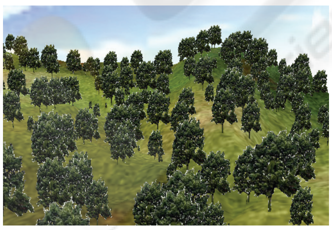

Figure 6: Scene rendered at the age of 300.

5.3.2 Visualization of Trees Distribution

Based on the forest evolving result we render two scenes at age of 50 and 300. As shown in Figure 5 and Figure 6, they're different in tree size and dense.

6 CONCLUSIONS

We extend the forest gap model with the terrain and the environmental factors are mapped into the tree grow function, and then imitate the influence of light, terrain and competition to the trees in the forest. We implement the system with VC++ 6.0 and OpenGL to simulate the trees growing in forest and the result is satisfying. The system will later be enhanced, as it cannot imitate the competition between different tree species, this need to be improved later.

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