Modeling and Visualization of symmetric and asymmetric plant competition

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Abstract
In this paper we describe a new method for the visual simulation of evolving plant communities, which involves, aside from the known symmetric competition for resources also asymmetric competition. Asymmetric competition takes place if plants differ in their size and/or species. The discrete simulation methods proposed in this work help to visually simulate complex plant ecosystems for computer graphics.

1. Introduction

Simulation and visualization of plant competition is an important research field, not only in ecology where it helps predicting the future and the condition of ecosystems, but also in applications such as computational biology, landscape planning, and city architecture. Additionally, the methods can also be used to achieve beautiful realistic scenes that are used in the production of films, computer games and arts.

This work concerns itself with the modeling and visualization of large plant ecosystems, so that numerous natural scenes can be provided. In order to reach this goal, discrete methods for population dynamics are used. These methods incorporate individual states for the plants that describe their species, age and size. In contrast to the previous published methods, symmetric and asymmetric competition is covered that helps to simulate the interaction between plants of different size and species. Such interaction is important for visualizing borders between different ecosystems as well as complex systems that consist of many different plant species.

Since especially the interaction between ecosystems is visually important, often we are more interested in the forest border than in its interior. We think that asymmetric competition is an important factor for the visually accurate simulation in computer graphics.

2. Previous work

The simulation and the visualization of plant competition on the basis of three-dimensional descriptions of geometry was treated during the last years by many authors. There are two different models in [LP02] to the large ecosystem simulation. The first is the local-to-global in which the ecosystem is simulated through individual plant competition for resources. The second is the global-to-local model. Here we focused on the first model and developed a new method for the efficient and stable simulation of individual plants in a population. Before we go into details, we first focus on modeling individual plants.

The realistic modeling of individual plants has a rather long history in computer graphics. Generally, it can be divided into two important categories. The first category tries to model the plant morphology without any knowledge of the internal processes. The second tries to achieve a realistic shape of a plant by simulating the internal processes. In-between we can find many methods that incorporate the internal behavior of plants to a lower or a higher extent. An overview of various methods is given by [DL04], a tutorial on plant modeling can be found in [Jon02].

Sophisticated models for plant ecosystems were mentioned in the context of the computer graphics by Mech and Prusinkiewicz in [MPgs]. Here, a forest landscape is modeled using random distributed positions; the plant lighting is approximated and then used for interaction.

In [DHP*] a discrete population model is introduced that is able to simulate the competition of several species using

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a relatively simple graphical computation. However, the authors achieve realistic images for scenes consisting of thousands of plants. Lane and Prusinkiewiz [LP02] extend L-systems to so-called multi-set L-systems, which are used for global-to-local and local to global simulation procedures. Here, a plant not only lowers the chance for other plants to grow in its direct neighborhood, but also increases the chance in an area around this neighbourhood. This helps to achieve typical distribution patterns for forests.

An interactive procedure that is based on particle systems, is introduced by Benes and Espinosa [BE01]. The objects that produce the particles reside in the 3D area. Other objects control growth, and affect the moving paths of the particles through the area.

Also in ecology a great amount of work has been done to simulate ecosystem development. However, mostly continuous simulation methods are used that allow describing the plant density in a given region, but not individual plant locations. Basic work on discrete methods is described by [BBHG02]. Here a model is introduced that works for graphical abstraction of plant sizes. The details that are necessary for simulating the growth of an individual plant in a plant community, are discussed in [CDN02]. In [Aik04] the competition for resources between homogeneous plants and in [AP03] the relationship between the yearly growth of a plant and the population density is discussed.

In the following, we distinguish between two cases: the symmetric competition σ_{ij} (i and j are Plants), and the asymmetric competition α_{ij} between plants. While in the previous work only symmetrical or asymmetrical competition was considered, here we include both cases . Firstly, we describe the general model and discuss the behavior of the individual plants, including growth and seeding. Secondly, we discuss competition. A system description is given, and results are discussed.

3. Competition among Simulated Plants

Our model is based on the so-called FON model (field-of-neighbourhood) which is described in [BBHG02, UH00]. The FON describes a circular zone of influence around a plant whose radius determines the distance up to which the plant interacts with neighbouring plants. This radius is not primarily dependent of the size of the plant, but also depends on the soil, i.e. by the amount of nutrition the plant needs and how much space is necessary to provide this nutrition.

The extent of this zone is specified by a nonlinear function of the basal radius R_{basal} of the plant (see [BHG02] and also Figure 1(a)):

$$R_{FON} = d \left(R_{basal} \right)^{b} \qquad (1)$$

where d and b are constants, typically d has the range of $[12..133]$ and $b \in [1.2..2.3]$.

The influence of the individual plant to its neighbours
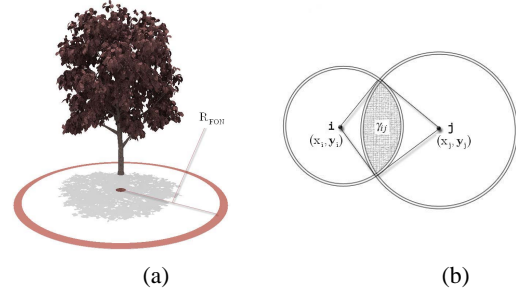

Figure 1: *a) The zone of influence (R_{FON}) depends on the diameter of the trunk base; b) The geometry of the spatial competition between the individual plants i and j with position (x_i, y_i) and (x_j, y_j) is a function of the overlapping area γ_{ij}*
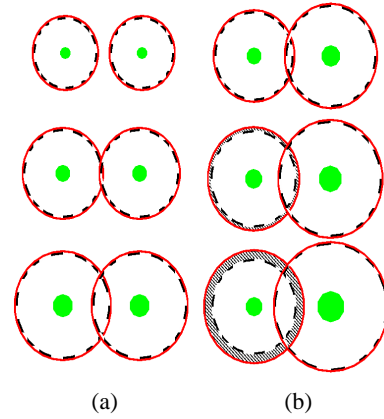

Figure 2: *Difference between symmetric and asymmetric competition: a) two plants of equal size behave in a symmetric way: both receive the same amount of nutritions/light and grow equally; b) if one plant is smaller, it receives less nutritions/light, and the effect is a reduced growth rate (indicated by the dashed line)*

is now described in a phenomenological way. It can be divided into two categories: the symmetrical competition and the asymmetrical competition [Aik04]:

1. Symmetric influence or symmetric competition σ_{ij}: competition is a double-sided interaction in which the resources are equally divided between the competitors. These individual plants share resources [BT96].

$$\sigma_{ij} = \frac{\gamma_{ij}}{2} \qquad (2)$$

Here i and j are the plants and γ_{ij} is the overlapping area as shown in Figure 1(b).

2. Asymmetric influence or asymmetric competition α_{ij}: competition here is a one-sided interaction. This means that the individual plant gains all the resources of the
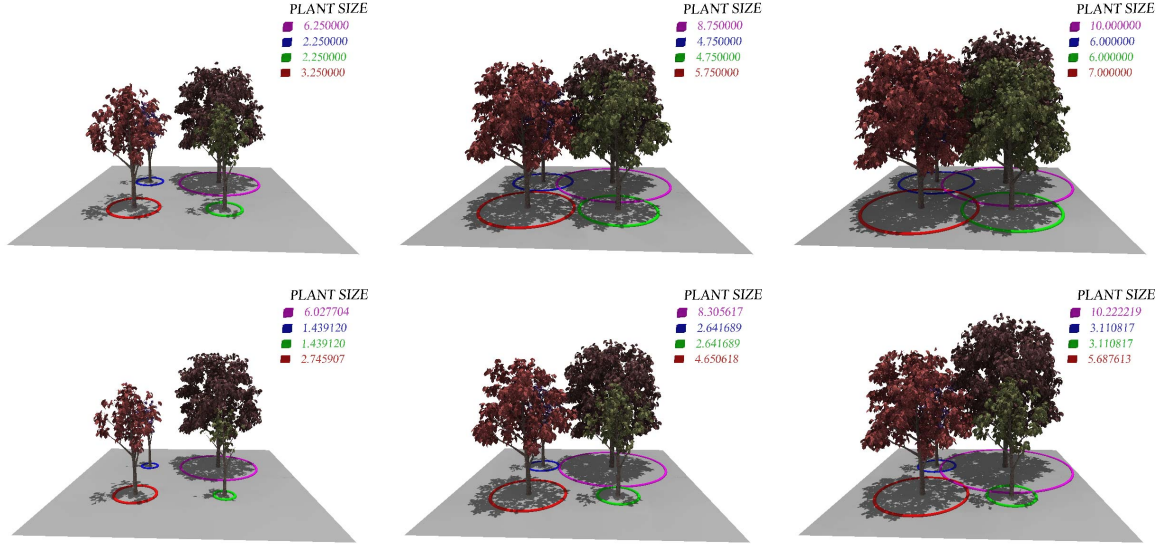
Figure 3: *Upper row: no competition, lower row: symmetrical and asymmetrical competition. The smaller (green) plant is dominated by the other plants.*

overlapping area and the other plants do not have the chance to gain resources [Wei90].

$$\alpha_{ij} = \begin{cases} \gamma_{ij} & : & f_i > f_j \\ \gamma_{ij} \text{ or } 0 & : & f_i = f_j \\ 0 & : & f_i < f_j \end{cases} \quad (3)$$

f_i and f_j are the respective FON radii. The above equation simply states that the plant with larger radius receives all resources. The general competition φ_i is a weighted combination of symmetrical and asymmetrical competition. It is written as:

$$\varphi_i = p\,\alpha_{ij} + (1-p)\sigma_{ij} \quad (4)$$

with $p \in [0..1]$ being the weighting factor.

In Figure 2 three different stages are represented for asymmetrical and symmetrical competition among plants. The left column shows the difference between no competition and symmetric competition. In the right column the asymmetrical interaction is shown in contrast to the growth without competition. In this case one plant growths much less. In Fig. 3 some trees are shown in the asymmetric competition. In the lower row three of the trees are dominated by the fourth one and as a result they grow less.

In combination with a growth model, The asymmetric competition can be used to create realistic plant communities. Starting with an initial configuration, the system is able to automatically create realistic differences in size and to react to the death of individuals appropriately (see Sect. 5).

4. Growth of Individual Plants

The growth of the individual plant depends on the condition in their neighboring plants and their actual size. It can be described by the Richards growth model [Ric59, Van89, GBFP01] and is written as follows:

$$\frac{dv_i(t)}{dt} = \begin{cases} \frac{k}{1-\delta} f(v_i(t),a) \\ \qquad ((\frac{1}{w_m}\sum_{j=1}^{n} v_j(t)\varphi_i)^{\delta-1} - 1) \\ \qquad\qquad\qquad\qquad \delta \neq 1 \\ k f(v_i(t),a) \\ \qquad (log(w_m) - log(\sum_{j=1}^{n} v_j(t)\varphi_i)) \\ \qquad\qquad\qquad\qquad \delta = 1 \end{cases}$$

$$(5)$$

In this equation w_m is the final size of a plant, $v_i(t)$ is the size of the plant i in relation to time t, k is a growth parameter, and $\frac{k}{1-\delta}$ is the growth rate without competition (see Fig. 4 for typical values of the constants). The effect of the size-asymmetry on the growth can be included into the Richards growth model by modeling the growth function of the individual plants according to their size:

$$f(v(t),a) = \begin{cases} 1 & : & a = 0 \\ v(t)^a & : & a > 0 \\ 1 \text{ or } 0 & : & a = \infty \end{cases} \quad (6)$$

Here the parameter a determines the amount of asymmetry in the sizes of the plants and also the slope of the growth function [SF95, Dam99, WWJ99, Dam01].

The plants reproduce themselves in the model by distributing their seeds. Individual plants start to reproduce once they have reached a certain size. The seed production

increases simultaneously with the plant size, until a maximum size has been reached. Seeds are scattered locally around the mother plant. For the calculation of a seed position we use a two-dimensional Gaussian probability function:

$$p(r) = e^{\frac{-r}{\lambda}} \tag{7}$$

with λ being the main value of the probability function, and r being the defined distribution distance.

The mortality of plants, which are influenced by high pressure of competition is higher than solitaire plants. We can define this mortality risk as the average plant size over the last five iteration steps [BBHG02]. In the simulation, actual and average size of the individual plant v_i at the time t is defined as follows:

$$v_i(t+1) = v_i(t) + \frac{dv_i(t+1)}{dt}, \ \overline{v_i}(t) = \frac{1}{5}\sum_{l=0}^{4} v_i(t-l) \tag{8}$$

were $v_i(t)$ denotes the size of the plant v_i at the time of t. If the average size $\overline{v_i}$ is below a certain threshold over a time period because of neighbour competition, we assume that the individual plant dies. Consequently, plants that have reached their maximum age must also gradually die.
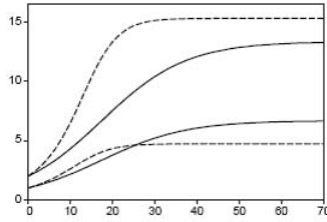

Figure 4: *Richards growth model for two plants affecting each other. For two initial sizes of one and two, resp., two levels of size asymmetry are denoted. Full line: $a = 1, w = 10, k = 0.1, \delta = 2$. Dashed line: $a = 1, w = 10, k = 0.0667, \delta = 2$.*
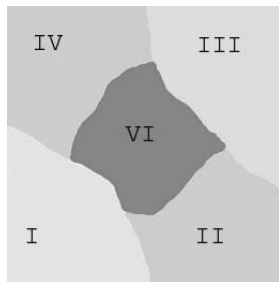

Figure 5: *The varying density of the grey scale values represents the differences in quantity of ressources in the ground and in the climate. Area I is hereby the best area, following are areas III, II, IV, VI.*

5. Simulation system

The modeling of the competition enables us to create biologically plausible systems that react appropriately to external forces. Before we demonstrate the system behaviour using a set of situations, we first describe the system outline. The discrete simulation is represented by the following system data:

A. the number of newly produced plants by the mature plants. The plants are added to the simulation for each simulation step.
B. the maximal size of the plant.
C. the average growth rate of the plant.
D. the amount of nutrition in the ground as a map of different grey scales controlled by the user. Figure 5 shows a sample map with five regions of different nutrition saturation.

Using the simulation results, we can produce an animation of the ecosystem development. Usually the plants are modeled using the Xfrog software system [DL97], and are then imported into the system. In the rendering step, the plant models are exported to the POVRAY raytracing software.

If an initial map such as the one shown in Fig. 5 is given, the fon radii of the plants differ much in respect to the actual position. At places with a low amount of ressources, the radii are much larger than at other places meaning that the plants compete much earlier about the necessary ressources. In a first test 100 plants of the same species are randomly distributed on an area of $200m \times 200m$. Each plant is represented by two circular areas, whereby the first represents the size of the plant, and the second the distance R_{FON}, which denotes the needed surrounding space of the plant. In the system, the vitality of the plant $\overline{v}$ (according to Eqn. 8) and its age are stored additionally. Fig 6 shows the development of such a population using the spatial growth conditions given by Fig. 5.

After the simulation and visualization of the competition between the plants that are of the same species, we extend the system to deal with two plant species. The plants can multiply themselves during a certain time and produce more plants. In this system, additionally for each plant its type is defined as well as the number of seeds. In Fig 8 we show how the plants of the smaller species are affected by the larger ones, meaning that in the vicinity of the big species the smaller plants are not able to develop.

Finally, we show how a population reacts if plants die. In this case, the neighbours that are no longer dominated by those plants, are able to develop, and the population again achieves an uniform look. this is shown In Fig 9. Such reactions are difficult to create in other simulation models.

6. Conclusion

In this work we presented a system for simulation and visualization of the competition between the plants for resources.
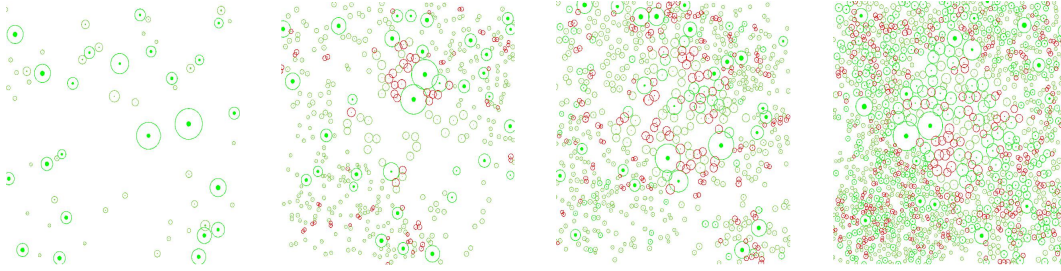
Figure 6: *System development of one population with asymmetric competition. The bright green circles represent plants that are very old. Plants marked with red circles have strong competition.*
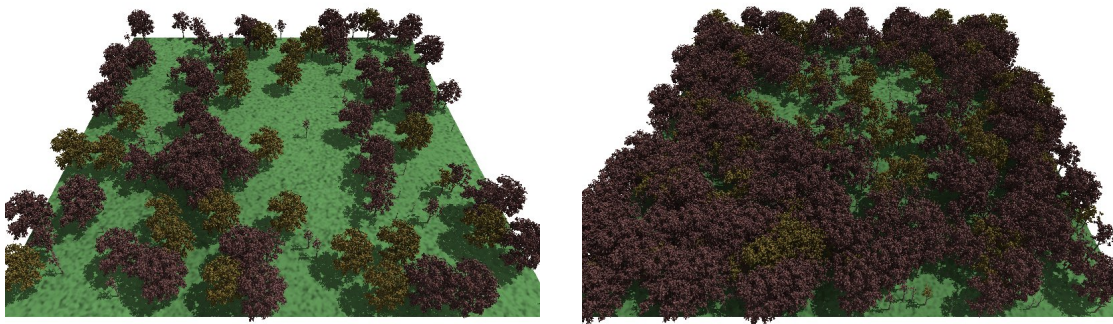

Figure 7: *Rendition based on Fig. 6 that shows that plants in the center area are sparsely distributed due to the limited amount of ressources.*

Figure 8: *Asymmetric competition between two species of different size. The red circle indicates the region where the second species is not able to develop because of the competition.*

In contrast to prior results, we simulated the asymmetric plant competition. In our method we propose a graphical representation of the area needed by an individual plant in order to compute growth and development during competition. We tested our system for a number of scenes, including populations of one species as well as the competition between different species. Using this kind of simulation, animations of developing ecosystems can be produced with a higher degree of realism.

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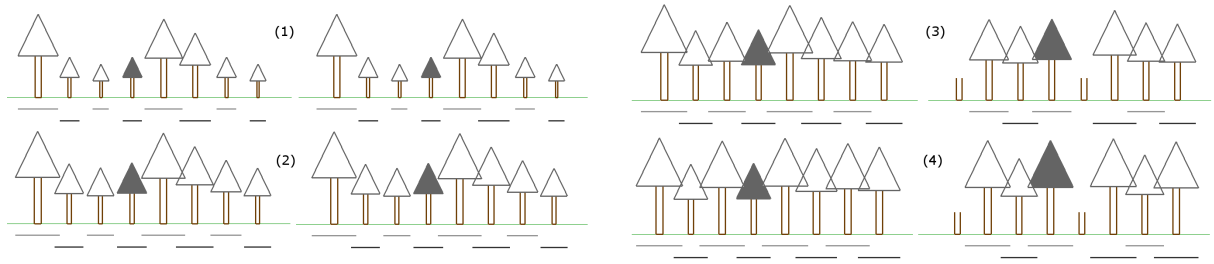
Figure 9: *Reaction of a (stylized) population to the death of individuals. Side by side four simulation steps are shown. In the right system in step four two individuals die. The system changes its shape accordingly.*