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THE ALGORITHMIC BEAUTY OF PLANT ROOTS

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Abstract. Dynamic root growth simulation is an important tool when analysing the mechanisms within the rhizosphere. The concentration of nutrients in the soil as well as water content strongly depends on the root structure. On the other hand root growth is effected by the nutrient concentration and water supply as well as other soil parameters. As a result realistic root growth models are often coupled with models describing the plant-soil interactions. In this paper we present an L-System algorithm which makes it possible to easily create 3-dimensional geometries of growing plant root systems. Furthermore we discuss possibilities of coupling these root growth system models with arbitrary models describing plant-soil interaction. The model is implemented in Matlab, which makes it easy to combine it to existing Matlab or Comsol models.

1 Introduction

In modelling and simulation of plant-soil interactions accurate root growth models are of major importance. In many cases these models are coarse approximations of growing root systems. Many models directly compute root length densities without including root architecture or branching structure. These densities then provide the basis of source and sink terms to nutrient uptake or exudation models ([1], [2]).

There already are some powerful discrete root growth models ([3], [4], [5], [6]). However it is hard to completely understand their behaviour and couple them to arbitrary uptake and exudation models. Our aim is therefore to develop tools that can easily set up root growth models and link them to arbitrary uptake or exudation models implemented in Matlab or Comsol. It is important that global root system parameters from literature or experiments can be included in the present model. As a result the code is kept simple by using the notation of parametrized L-Systems and therefore can be easily adapted to several applications.

2 L-Systems

In computer graphics the complex geometry of plants is often described by L-Systems. L-Systems describe highly branched structures in a very elegant way and derive amazing pictures from simple production rules (see e.g. [7]). In this work time-dependent L-Systems are used to describe the growth of root systems. In this application the parameters that have been derived from literature or experiments can be used to describe time dependent growth accurately.

L-Systems are rewriting systems. All letters of an initial word usually denoted as ω are replaced according to production rules. The production rules are applied to each letter of the word, this is performed recursively n times to achieve an L-System of the n^{th} generation. The resulting string is interpreted graphically. For example the initiator ω and the production rule for X

$$\omega = \quad X, \quad X \rightarrow F \; - \; [\,[\,X\,] \, + \, X\,] \, + \, F\,[\,+\,F\,X\,] \, - \, X \tag{1}$$

create figure 1. Note that the letters $F, +, -, [,]$ are replaced by themselves and are used for the graphical interpretation of the string (see appendix A for a list of turtle graphic commands).

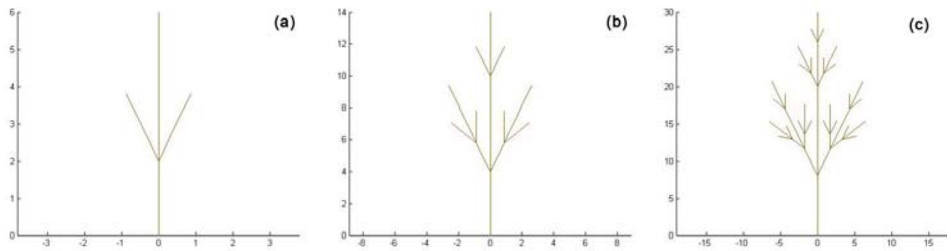


Figure 1: The 2^{nd}, 3^{rd} and 4^{th} generation of an L-System (reproduced from [7])

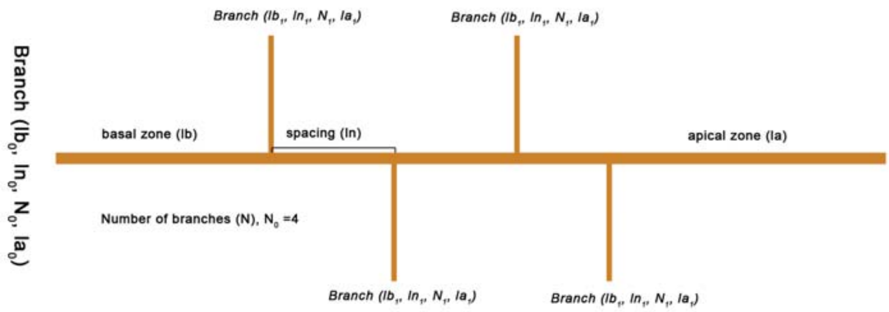


Figure 2: An illustration of the self similar character of plant roots

3 L-Systems for root systems

Considering a root system it is important to exploit its self similar structure (see figure 2). Every single root of a certain order produces branches of successive order and is divided into three zones: the basal as well as the apical zones near the base and the tip of the root where no branches are produced, and the branching zone where new roots of the next order are created. The corresponding parameter values depicted in figure 2 determine the length of each zone predetermined for every order i.

According to this branching structure our L-System model has a production rule for the basal zone, which is followed by the production rules for the branching zone and the apical zone. When new branches are created they begin to grow after a certain time delay in order to wait for the apical zone to develop. The production rule to create a new branch sets up the production rules describing the different root zones.

It would go beyond the scope of this article to describe every production rule in detail, but we emphasise that the Matlab code is freely available[1] and can be easily analysed and adapted. Every production rule has an Matlab file with corresponding name. In the following we discuss the parameters which are used within the production rules.

For every order of the root system several parameters are required. In our model for every parameter the mean and standard deviation must be predetermined. If the standard deviation of a value is not known it can be simple set to zero. The parameters describing the dynamic, length and interconnection of the root system are given by:

Mean	SD	Description	Dimension
r	r_s	initial growth speed	[cm/s]
l_b	l_{bs}	length of basal zone	[cm]
l_a	l_{as}	length of apical zone	[cm]
l_n	l_{ns}	spacing between branches	[cm]
n_{ob}	n_{obs}	number of branches	-

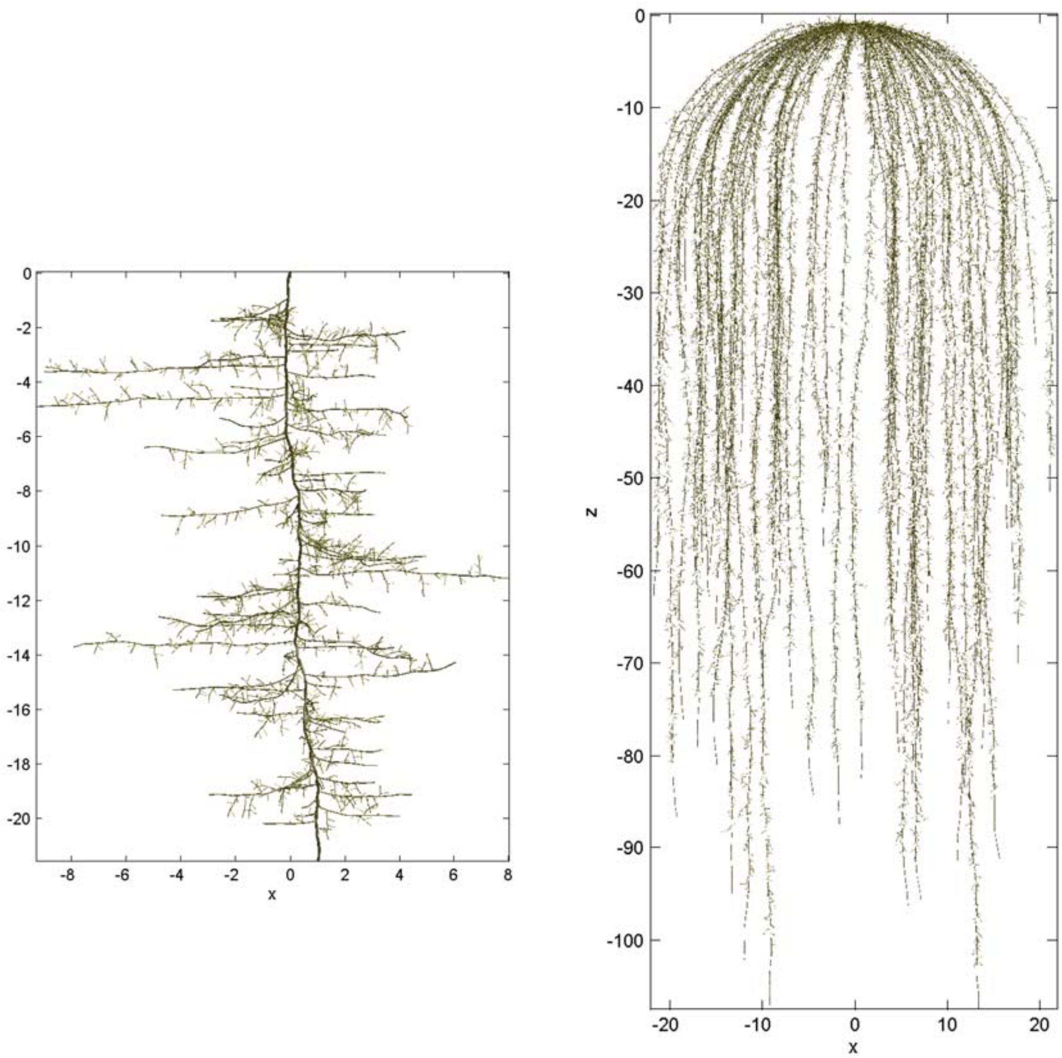
To obtain a 3-dimensional geometry the following geometrical parameters are needed:

Mean	SD	Description	Dimension
a	a_s	root radius	[cm]
θ	θ_s	branching angle from predecessor	radian
$color$	-	colour of the root	RGB

Note that the root radius can be a function of root length, e.g. getting smaller towards the root tip. However for many applications it is sufficient to assume a constant radius per root order because the variation of root radius is small compared to plant scale. Moreover quantitative values are often not available.

With these basic parameters an idealised root system is described, in which every root tip grows straight ahead. To include effects that arise from gravitation, soil properties or nutrient availability more parameters are included.

[1] A link can be found on `www.boku.ac.at/rootmodel/further`



(a) Root system of Anagallis

(b) Root system of Maize

Figure 3: Two different simulated root sytems.

4 Results

For our simulated root system we used parameters from literature and compared results to the illustration of Lore Kutschera [8]. To obtain realistic root systems it was important to include morphological effects like geotropism, which is the tendency of a root tip to grow downwards and plagiotropism, which is the tendency of the root tip to grow horizontally. Figure 3 shows two root systems: one of Anagallis and one of Maize. In the root system of Anagallis the order zero root shows a strong gravitropism, while the order one roots have a strong plagiotropism, see figure 3(a). Maize consists of a large number of order zero branches which tend to grow downwards due to a strong geotropism, see 3(b). The two root systems are similar compared to illustrations found in literature.

5 Conclusion

In this article we have presented a dynamic root architecture model that is based on L-Systems. It has been shown that it is easy to set up arbitrary models of a growing root systems and to derive their 3-dimensional geometries. This is done by using parameters found in literature or obtained by experiments. The resulting figures have been compared to to illustrations done by Lore Kutchera [8]. The Matlab code is freely available[1] and can be easily adapted and extended by changing parameters or by adding or rewriting of production rules.

[1] A link can be found on `www.boku.ac.at/rootmodel/further`

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8 Appendix A

The resulting string of a parametric L-System can be graphically represented using a Turtle graphics. The letters of the string represent the following commands (after [7]):

Letter	*Description*	*Parameter names*
F	Draws a segment and moves to new position	length
#	Sets the width of the following segments	width
C	Sets the colour of the following segments	color
+, -	Turns left or right	delta
&, ˆ	Pitch down or up	delta
\, /	Roll left or right	delta
|	Turn around	-
[,]	Pushes and pops the turtle state	-

The segments are normally straight cylindrical tubes or lines. The results can be either plotted to a Matlab figure (`drawString3D.m` or `drawString3Dtube.m`), or to DXF or STL files (`drawString3DDXF.m`, `drawString3DSTL.m`). Further COMSOL Multiphysics geometry can be produced directly (`drawString3DComol.m`) or by first meshing the geometry externally (`ImportMeshComsol.m`) and then importing resulting the mesh.