C-ROOT: a general continuous model of root growth based on root architecture and development of plants

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Abstract

Modelling and simulating plant root growth in connection with soil water and nutrient transfer is an important challenge that finds applications in many fields of research. If root architectural models are suited for making the functional link between plant growth and soil (Jourdan and Rey, 1997; Pagès *et al.*, 2004), at the individual scale, continuous approaches (Dupuy *et al.*, 2010) based on aggregated variables and density functions, i.e. topologically not explicit, can be necessary to simulate root growth at the stand/crop level. The C-ROOT model presented here belongs to this second category. It is a general continuous root growth model that aggregates architectural and developmental information. The model was implemented in C++ language and tested on three case studies representing different root growth patterns.

Model description

C-ROOT is a continuous model that describes the time and space evolution of $u(x,y,z,t)$, the number of apices per unit of volume, through the equation:

$$\begin{cases} \frac{\partial u}{\partial t} = R(u) + A(u) + D(u) \\ \nabla u.\upsilon = 0 \ \text{(Neumann boundary conditions)} \end{cases}$$

The model is described by **reaction**, **advection** and **diffusion** operators (R, A, D respectively), which are related to **root growth processes** such as **primary growth, branching and mortality** (Bonneu *et al.*, 2012). In the equations below β and μ are the branching and the mortality coefficients, v and D are the advection and diffusion coefficients, respectively. The reaction operator gives the quantity of apices produced in time, whereas advection and diffusion are conservative operators that spatially distribute the whole apices within the soil.

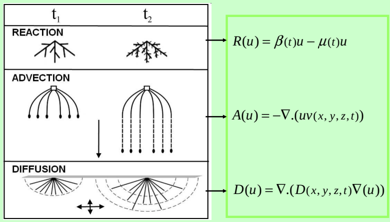

Figure 1 - Analogies between root processes and physical operators

Numerical method

Operator splitting techniques were used to solve and fit the model (Hundsdorfer and Verwer, 2003). The **calibration method** is decomposed into two steps. A temporal calibration of the reaction parameters is first made for each iteration time. Then, the advection and diffusion parameters are optimized on various time intervals, corresponding to development phases of the root system. The optimization process of these two operators is made by using a Levenberg Marquardt method.

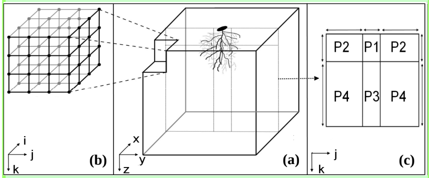

Figure 2 - Discretization of a 3D soil sub-domain. (a) Representation of a 3D soil sub-domain in which the root system grows; (b) the domain can be discretized in order to extract the number of apices created by the growing root system for each node. Nodes of the mesh are indexes by i, j, k in the directions x, y and z, respectively ; (c) Splitting of a 2D soil subdomain into areas where the advection and diffusion parameters take different values (P_1, P_2, P_3, P_4), depending on the local growth strategy.

Case studies

Various strategies concerning the emission process of root axes can be presented according to the classification of Canon (1949).

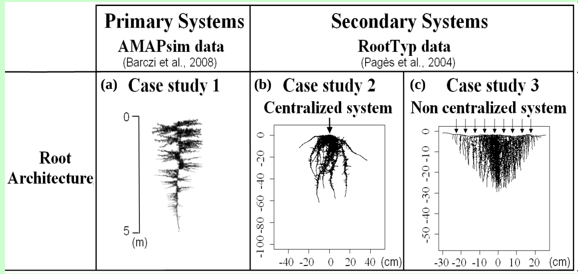

Figure 3 – Case studies representing **Primary root systems** (originating from a branching seminal root) and **Secondary root systems** (mainly formed from adventitious roots, continuously emitted from shoot). (a) case study 1 corresponds to the main horizontal roots of **Eucalyptus root systems** observed in the field (Bonneu *et al.*, 2012) ; (b) the case study 2 was based on observed **maize root systems**; (c) the case study 3 was based on a graphical representation of **root systems having non-centralized emission process,** where roots are distributed along a rhizome network such as the root system of *Achillea millefolium* (Pagès *et al.*, 2004), provided by Kutschera (1960).

Simulation results

Case Study 1

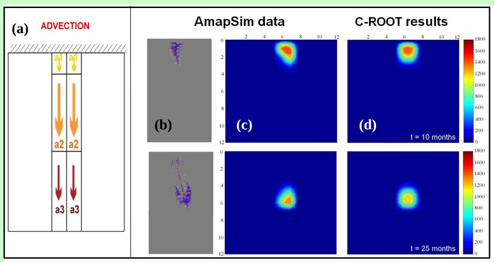

Figure 4 – Root data and simulations of case study 1. (a) soil partition for the calibration of the advection operator; (b) simulation results of Eucalyptus root growth provided by the AMAPsim software; (c) density of root number extracted from (b); (d) density functions calculated by C-ROOT. Only advection and reaction were needed in order to simulate growth and death of roots born by the horizontal roots (Bonneu *et al.*, 2012).

Case Study 2

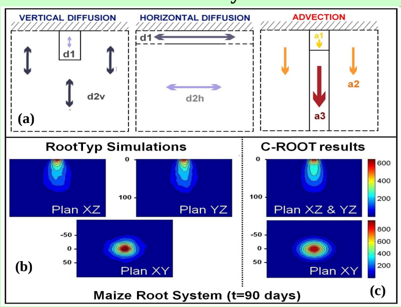

Figure 5 – Root data and simulations of case study 2. (a) soil partition for the calibration of the diffusion and advection operators; simulation results of Maize root growth provided by the RootTyp software (b) and by C-ROOT (c).

Case Study 3

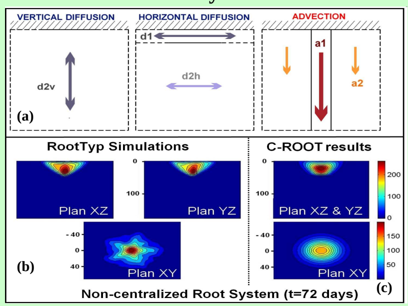

Figure 6 – Root data and simulations of case study 3. (a) soil partition for the calibration of the diffusion and advection operators; simulation results of non-centralized root growth provided by the RootTyp software (b) and by C-ROOT (c).

Conclusion

Each case study was composed of two main ontogenic phases: an important production of root apices due to an intensive branching effect in a first phase, and the decrease in root production until the beginning of the death of the entire system in a second stage. In each phase, the soil domain was split into sub-domains, in which the advection and diffusion parameters had specific values, depending on the local growth strategies. This soil splitting allowed the model to generate various root architectures and developments. Results reproduced quantitatively the dynamic evolution of root tip density distribution with a good accuracy.

The continuous approach allows C-ROOT to be easily coupled with other physical models, also based on continuous formulation, *e.g.* nutrient and water transfer. In addition, the computational time consuming is strongly reduced in the continuous approaches compared to the architectural models. Therefore, the model is suitable for the simulation of root growth at the population scale.

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