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Orange tree simulation under heterogeneous environment using agent-based model ORASIM

Hongchun Qu [a,d,*], Youlan Wang [b], Linqin Cai [a], Ting Wang [a], Zhonghua Lu [c]

[a] *Key Laboratory of Network Control and Intelligent Instrument (Chongqing University of Posts and Telecommunications), Ministry of Education, Chongqing 400065, China*
[b] *Chongqing Electric Power College, State Grid, Chongqing 400053, China*
[c] *Chongqing Agriculture Science Institute, Chongqing 400055, China*
[d] *Plant Ecology Group, Institute for Evolution and Ecology, Tübingen University, Auf der Morgenstelle 3, 72076 Tübingen, Germany*

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ABSTRACT

This paper presented an agent-based functional–structural model ORASIM for orange tree growth simulation. In ORASIM, detailed geometry, carbon/water acquisitions and expenses, as well as their dynamics are integrated into individual metamer/root agents. The nested-list of metamer/root agents forms a growing, three-dimensional orange tree structure. After model parameterization and validation using field data of orange tree growth, main features of tree functioning, i.e., morphological and physiological responses to environmental heterogeneity on different time scales have been investigated. It demonstrated that, using ORASIM, the phenotypic plasticity can be fully resulted from interactions between agents. Meanwhile, the output of ORASIM shows a good agreement for the characters of shape, branch pattern and other physiological features between the simulation and the real growth orange trees.

1. Introduction

The complex architecture and physiological processes of trees as well as their phenotypic plasticity in response to environmental heterogeneity [4,89], have attracted scientists to devise approaches to capture and simulate these complexities in different ways. During the long history of tree growth modeling [80], many kinds of tree models focusing on function and structure aspects have been developed. Some models utilize statistical [2] or empirical equations [45,66], some are combined with pipe theory [69], some models focus on a tree's physiological growth processes [43,86,46,38,37], while others focus on the structural pattern [24,31,53,54,35,36,25,26,55] of the tree crown as well as the root system [81,10].

Among tree growth models ranging from simple to complex, physiological processes and structural morphology are two critical properties that must be accommodated. Both process-based tree models (PBTMs) and morphological modeling approaches undergo limitations [56]. These two basic approaches, however, to a certain degree complementary, can be combined into a better modeling approach by reducing the limitations of each. Such is what is called functional–structural tree modeling (FSTM) [56,49–51,70,62–65,30,88,84]. The functional–structural tree model bridges the gap between PBTMs and tree architecture models by depicting an accurate 3-D perspective of plants as an aid for analyzing plant behavior. Most FSTMs represent a tree as a collection of elementary units such as bud, leaf, internode, branching point, and stem segment

* Corresponding author. Current address: Plant Ecology Group, Institute for Evolution and Ecology, Tübingen University, Auf der Morgenstelle 3, 72076 Tübingen, Germany. Tel.: +86 137 0837 2296.
E-mail address: hcchyu@gmail.com (H. Qu).

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[49,62,25], more common in modular perspective, the metamers [67,73,74]. In such models, both morphological structure and physiological processes can be integrated in the same unit.

Nevertheless, most FSTMs simulate tree growth using specific growth rules [70,71,49–51], e.g., manually designed L-system for controlling the iteration of elementary units. Growth rule design for specific type of tree is a time-consuming work. Not to mention that different types of tree have different branching patterns [1]. All individual trees in nature are distinct entities exhibiting behavior typical of all complex organisms [79] which development held in balance by complex cause–effect interactions, i.e., internal physiological process and external environmental heterogeneities. These complex behaviors have no identifiable center of tactics, as opposed to strategic, control. Traditional FSTMs aforementioned can not model these emergent features effectively [58]. New modeling paradigm, such as the teleonomic approach that can emerge complex behaviors [5] of tree development from simple and "bottom-up" perspective [61] is a considerable option.

In recent years, tree models have been increasingly concerned over emergent properties of growth. A CA (cellular automata) based simulation of plant growth and resources competition was developed [8,9,23]. The CA-based approach and ALMIS [16] both use the teleonomic modeling approach to reproduce emergent properties (i.e., the phenotypic plasticity) on global plant level through the interactions from individual organs. However, the limitations due to rough-organ design make them difficult to integrate complex knowledge and mimic the intelligent behaviors of tree growth. Moreover, the rough diffusion approach to carbon transport used in the ALMIS as well as the primitive 2D simulation used in the CA-based model also is shortcoming that needs to be improved. An object-oriented FSTM, the GRAAL [13,14] was developed to simulate and analyze emergent growth resulted from interactions between morphogenetic processes and assimilate partitioning during the vegetative development. Physiological and morphological knowledge is formalized at the organ level. Main features of plant functioning (e.g., kinetics of root/shoot ratio for carbon, changes in priority between organs and plant plasticity to carbon availability) have been reproduced at the whole plant level. Another metamer-based FSTM [73,74] was developed to explore how light might influence the ontogenetic patterns in three-dimensional (3-D) growth of trees. However, both GRAAL and model proposed by Sterck et al. [73] still need tree level operations for carbon allocation rather than physiological rules integrated on metamer level.

This paper presented an agent-based functional–structural model ORASIM for orange tree growth simulation. ORASIM inherited from a previous plant model [60] for simulating growth of herbs. However, it is has been extended here to simulations of more complex plants such as orange tree. New functions such as light interception component, discrete transport-resistance model for carbon transport and meristem state transitions for branching pattern control have been integrated. In ORASIM, detailed geometry, carbon/water acquisitions and expenses, as well as their dynamics are integrated into individual metamer/root agents. The nested-list of metamer/root agents forms a growing, three-dimensional orange tree structure. After model parameterization and validation using field data of orange tree growth, main features of tree functioning, i.e., morphological and physiological responses to environmental heterogeneity on different time scales have been investigated. It demonstrated that, using ORASIM, the phenotypic plasticity can be resulted from interactions between agents. Moreover, the output of ORASIM shows a good agreement for the characters of shape, branch pattern and other physiological features between the simulated orange tree and the real growth one.

The main objectives were:

(1) To present the functional and structural features of the agent-based model ORASIM for orange tree growth simulation.
(2) To test the effect of variable resource captures (e.g., photosynthesis, and water uptake from soil) on yields and other biological properties for orange tree.
(3) To examine the tree branching structure resulted from meristem state transition among metamers.
(4) And to illustrate the phenotypic plasticity (i.e., response to environmental heterogeneity) emerging at the global tree level due to locally formalized knowledge on metamer/root level.

2. Model description

2.1. Simulation framework

ORASIM is an agent based orange tree model. The above-ground part (shoot system) is composed of nested-list metamers which are modeled as individual intelligent agents. The below-ground part (root system) consists of nested-list root agent. Each individual agent possesses geometry (Table 1) as well as functional structure (Fig. 1) to perform physiological rules.

The simulation time step is the time period for an individual cycle of physiological process being modeled. The cycle of physiological process repeated every hour. At the end of every 24 simulation time cycles (an interval of 1 day), the OpenGL-based 3D graphic engine scans individual metamer/root agents using the breadth first approach to interpret their topology and geometry to 3D graphics by reading their status. Shapes of individual organs in metamer/root are represented by predefined Bézier-surface-based mesh objects stored in an organ mesh library. The graphic engine with organ mesh library is similar to the Turtle interpreter implemented in L-Studio [57].

ORASIM was programmed in Visual C++ environment. All agents are running in a simulation engine (Agents Kernel) which is the core of the ORASIM. The Agents Kernel provides the runtime environment such as memory management, communication services as well as geometric mapping, etc. The development of orange tree is modeled as the evolution of agents