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Light interception efficiency analysis based on three-dimensional peach canopy models

Liyu Tang *, Can Hou, Hongyu Huang, Chongcheng Chen, Jie Zou, Ding Lin

National Engineering Research Center of Geospatial Information Technology, Key Laboratory of Spatial Data Mining & Information Sharing of MOE, Fuzhou University, Fuzhou 350002, China

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ABSTRACT

Light interception capability is a critical factor affecting the growth, development, fruit yield and quality of fruit trees; thus, it is beneficial to cultivate optimal canopy types with high light interception efficiency. In this study, we present a quantitative method of analyzing light interception by tree canopies based on a virtual plant model. A detailed three-dimensional (3D) peach model with a natural growth shape was reconstructed and then the branches in the model were pruned to generate canopies with an open center form. These models were used to calculate the light interception and corresponding net photosynthesis. A solar radiation transfer model was used to determine the radiation intensity at the top of the canopy, and a ray tracing algorithm and turtle algorithm were utilized to simulate the spatial distribution of direct and diffuse radiation, respectively, in the tree canopy and obtain the photosynthetically active radiation (PAR) for each leaf. In the final step, we applied the photosynthesis model to calculate the canopy net photosynthetic rate. To compare the light interception efficiency among various plant canopy shapes, the net production rate at the whole-canopy scale and the average net photosynthetic rate per unit leaf area were calculated. The simulation results showed that peach canopies with an open center form provided better results compared with canopies with a natural form in terms of light penetration and air ventilation. Our method supports quantitative analysis of light interception and use efficiency for different types of canopy architectures at each time step and for individual leaf units. The approach was implemented in the interactive parametric individual 3D tree modeling software ParaTree. The extended ParaTree software is useful for fruit tree management applications because it provides an intuitive tool that can assist in tree pruning and design for ideal canopy architecture types.

1. Introduction

The morphological architecture of fruit tree canopies affects light interception and distribution within the canopy. Light interception plays an important role in certain plant physiological processes, such as photosynthesis and transpiration; therefore, it affects the growth, development, fruit yield and quality of the plant (Da Silva et al., 2014; Génard et al., 2000; Wang et al., 2009). In the field of fruit tree cultivation and management, favorable light penetration and wind ventilation conditions in tree canopies are achieved through pruning and training systems; thus, the quality and quantity of flowers and fruits can be improved (Willaume et al., 2004). Canopy interception of photosynthetically active radiation (PAR) is an important parameter that can be used to indicate how much PAR is reaching the elements of canopy (Cieslak et al., 2008) and help analyze what is the optimal canopy form for certain fruit trees.

Traditionally there are two types of methods to study canopy interception of solar radiation. One is by field measurement; the other is through mathematic modeling. Field measurement can be used effectively, but it is time-consuming and labor expensive. And it is difficult to obtain data with high spatial and temporal resolution. The method is suitable for lower trees with small canopy as it is difficult to measure trees that are large and tall. The mathematic modeling method simulates how the radiation is transferred within plant canopy and makes some assumption or simplification approximately the canopy architecture. Radiation transfer model and geometric models of canopy architecture are used to estimate light interception in canopy. The canopy architecture model is represented as a turbid medium. This type of canopy models mostly assumes that leaves are small and random uniformly distributed in the canopy (Barillot et al., 2011) with leaf angle distribution function being ellipsoidal (Annandale et al., 2004) or spherical distribution (Rakocevic et al., 2000). The real architecture complexity is greatly reduced. Therefore, the approach is just a simplified approximation of real tree. In the medium, the radiation attenuation can be estimated by the Beer–Lambert law. Then, the light interception is usually calculated according to leaf area index (LAI) and extinction coefficient (Annandale et al., 2004). Although these methods provide a good estimation of total light interception within the canopy, they did not take the effects of local light intensity and canopy heterogeneity on the

* Corresponding author. Tel.: +86 13799421872.
E-mail address: tangly@fzu.edu.cn (L. Tang).

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light interception into consideration (Da Silva et al., 2014; Sarlikioti et al., 2011; Vos et al., 2009). To provide a better understanding of light distribution within canopies, new approaches have emerged that utilize detailed organ-based 3D models (Génard et al., 2000). 3D organ models can be reconstructed from data obtained by 3D digitizing instruments that perform measurements in the field or by software (e.g., L-system). Although the model is static and not applied to describe the plant development, it is useful for studying light distribution in the canopy (Iio et al., 2011; Vos et al., 2009); therefore, it is a good tool for assisting in the design of canopy types with high light interception (Su et al., 2008). Virtual plants can describe quantitatively accurate plant topology, geometry and organ position. Plant organs can be represented at every small individual 3D unit, and radiation transmission and interception among the units can be simulated with ray tracing or radiosity algorithms. Studies have used virtual plant approaches, and the light environment in the greenhouse and light interception on cut rose can be simulated to predict the local (per leaf) light absorption and photosynthesis (Buck-Sorlin et al., 2011). Han et al. (2012) and Da Silva et al. (2014) combined the 3D apple modeling tool MAppleT and light interception model VPlants to investigate the influence of the architectural parameters of apple trees on the light interception efficiency. In addition, the light interception efficiency of young *Cunninghamia lanceolata* canopies was calculated for growth simulation (Tang et al., 2012).

The photosynthesis characteristics and light interception capacity of peach trees have been studied and analyzed primarily by adopting traditional field measurement methods, and these analyses have produced meaningful observations and conclusions. In a study of the annual variation of photosynthesis rates of peaches with open center forms and spindle forms, the peak photosynthesis rate occurred in September (Wang et al., 2009). In young nectarine training systems, trees with the central leader form had the greatest light interception capabilities at the early stage of canopy formation (Gao et al., 2006). Virtual plant modeling has also been applied to perform growth simulations and light interception analysis of peach trees. L-PEACH is a functional-structural model that is based on L-system software, and it can simulate multiple-year tree growth. Tree growth has been described in a schematic or semi-realistic manner (Allen et al., 2007). A 3D peach model was constructed (Sonohat et al., 2006) by combining partially digitized tree structures with reconstruction rules for non-digitized organs. The tree model reconstruction approach provides a detailed 3D model for light interception analysis. 3D tree models have been used to simulate the photosynthesis of peaches according to the amount of direct and diffuse radiation (Génard et al., 2000). QualiTree integrates simple light interception and physiological process models to help design innovative horticultural best practices (Mirás-Avalos et al., 2011).

The objective of this study is to develop a quantitative analysis approach and tool for designing tree canopy types with high light interception efficiency based on virtual plants. We analyzed the light distribution in the peach canopy of varied forms and then evaluated the light interception. The interactive parametric individual 3D tree modeling tool ParaTree (Lin et al., 2011; Lin et al., 2012; Tang et al., 2011) was extended by integrating the radiation transfer model and photosynthesis model.

2. Materials and methods

2.1. 3D peach tree model reconstruction

Detailed 3D architecture models provide the foundation for canopy radiation transfer and distribution simulations, and the precision of the 3D model has a direct impact on the accuracy of the radiation simulation. Because leaves are the main plant organ that absorbs solar PAR, they are described explicitly. We focused on analyzing light interception in peach canopies with a natural form and open center form. The 3D canopy models were constructed using the interactive parametric individual 3D tree modeling tool ParaTree (Lin et al., 2011; Lin et al., 2012; Tang et al., 2011). In ParaTree, a tree model is composed of a main trunk, several branch levels, leaves and/or other organs. We used a set of parameters to describe the structure and shape characteristics of these components, and the parameters included the geometric and topological properties and morphological information. ParaTree allows user to build tree models for various species at different growth stages or different phenological phases by interactively modifying parameters. Moreover, this software can simulate branch pruning by interactively picking and editing a stem segment for constructing models of all types of canopy forms. Thus, ParaTree is a useful tool for designing canopy forms.

The key steps for generating a 3D peach tree model are listed as follows. (1) Acquire the morphological parameters, such as the tree height, crown width and branch length of the natural form and open center form peach trees through field observation and literatures study. For the trunk, the parameters include the basal diameter of the trunk, changes in diameter, length of the trunk and number of branch levels. The branch parameters are grouped based on the branch level, and the parameters for each level primarily include the distribution range of each branch level from the father stem, initial diameter of each branch level, changes in diameters, length of each branch level, etc. The leaf parameters include the size (width and length), shape, location, and distribution density. (2) Create a trunk and branch model based on the trunk and parameters mentioned above using the interactive parametric individual 3D tree modeling tool ParaTree. (3) Build a detailed 3D leaf model, as shown in Fig. 1(a), using 3ds Max, a 3D modeling software. The leaf model is represented in triangular mesh, and each leaf consists of 10 triangles in our study. To reduce the computational complexity, the same 3D leaf model is applied to the entire tree, and then the 3D leaf models are added to the branches. The 3D model of the natural form peach tree is constructed as shown in Fig. 1(c). (4) Modify the natural form model in ParaTree by editing branches and branch segments and then generate the 3D model of the open center form peach tree.

A number of local structural differences may be observed in the same tree canopy form. Therefore, two models of the open center form were produced from the same initial natural form model for comparison purposes. Model 1 of the open center form is created based on the model of the natural form, and it retains the four opening main branches and deletes all other branches (as shown in Fig. 2). Model 2 of the open center form is created based on the model of the natural form model as well; however, it retains three main branches, deletes one main branch with a smaller branching angle, and prunes all other branches retained in the first model. Fig. 2 shows the initial natural form model and two versions of open center models derived from the former.

2.2. Simulation of PAR distribution in a canopy

Canopy photosynthesis can be calculated as the amount of light absorbed by the canopy and the leaf photosynthetic response to light (Spitters et al., 1986). Incident light consists of solar direct radiation and sky diffuse radiation. The photosynthetically active wave band is generally in the range of 400 to 700 nm. Based on data from the literature, we assumed that PAR accounts for 40% of the global solar radiation energy.

Ray tracing and turtle algorithms were integrated into ParaTree; ray tracing is used to simulate direct solar radiation and turtle algorithms are used to simulate diffuse radiation. First, the light intensity in the field was calculated according to the geographical location using the atmospheric solar radiation transmission model. Then, the radiation transfer in the canopy was simulated to estimate the PAR for each leaf (or for each triangle). Consequently, the amount of total solar PAR intercepted by the entire tree per second and the average PAR photon flux density were calculated, and the values represent the average of