3D Visual Simulations of Chinese Flowering Cabbage

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Abstract: This paper presents 3D visual simulations, which consist of a statistical model and animated fly-throughs of Chinese flowering cabbage based on the essential principles of and practices of horticulture, to arouse interests for users in an entertaining way. These simulations reconstruct the stages of growth and development of Chinese flowering cabbage with geometric and topological characteristics, and show, for discussion purposes, how these animated fly-throughs can represent the interplay between stochastic and deterministic processes which are faithful to real plant growth and development under different operating conditions.

Keywords: Chinese flowering cabbage, 3D visual, Statistical model, Simulation, Topological characteristics.

1. INTRODUCTION

3D visual simulations can represent topological and geometric structure of plants [2, 8, 25]. Stretching beyond floriculture [1, 15], it reaches out to include pomology amongst horticulture in the interactive simulation [32]. Based on scientific data, every plant has been carefully reproduced as a realistic representation, according to the quality of computer graphics rendering [12, 20].

Lindenmayer system, which is a string rewriting system with formal grammar, can describe how annual plants develop deterministic structures by the production rules and can be used to generate self-similar morphology of reproductive and vegetative organs, leaves and flowers, for instance [5, 23, 18]. Consequently, it quickly become a powerful computational tool for biologists to identify patterns or relationships of biological entity with classic fractal (*e.g.*, molecule, organism, population, ecosystem, etc.). In some cases stochastic L-system，which describes plant growth process by using probability, has also been used to model the form and structure of biennial plants, but this is a time-consuming process as it is often difficult to find exact production rules for stochastic plant structures, fractals, and various other phenomena [22].

The architectural plant model (AMAP) focuses on the analysis and modelling of structure, development and diversity of a variety of plants [3, 4]. AMAP applies stochastic process to characterize morphological, functional and phylogenetical events, such as, branching, flowering, and fruit-setting, explore structure-function relationship of a plant species, interplant interactions and population dynamics [4, 6, 8].

This approach using architectural unit to make schematic representation of the plant is presented as a better interpretation of data recorded in a plant experiment, which means that plant growth simulation follows underlying patterns in which involved knowledge integration of genetic, physiological, ecological, and cultural mechanisms. The method is firstly introduced the concept of physiological age to simulate plant dynamic structure and function and clearly illustrated by de Reffye Philippe using an example of coffee tree at the plant modelling unit of CIRAD in southern France (Montpellier) [6]. This is useful to understand the role of each organ in light absorption, photosynthesis, translocation and accumulation of assimilates on plant development. Compared with analogous approaches [16], AMAP involves complex concepts and plant diversities [14, 24, 9, 10], which makes it hard to deal with interdisciplinary studies.

China has largest cultivation area and production of Chinese flowering cabbage [Sorghum bicolor (L.) Moench], in the world [5], which is one of the most consumed vegetables high in potassium, calcium, carotene (pro-vitamin A), folic acid, and dietary fiber in southern China. Compared with several other leafy vegetables, Chinese flowering cabbage prefers moist, fertile, sandy soil rich in organic matter [20]. In addition

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to variety, cultivation techniques, and weather conditions, plant density within a population influences the yield per unit area and can have an effect upon the yield each an individual plant, some aspects of which, such as the distribution of carbohydrates in leaves, shoots, and flowers, the light interception in leaf canopies, particularly the quantitative relationship between structure and physiological function of Chinese flowering cabbage still remain unclear [12, 13].

In the present study, a Markov chain, which is a stochastic model with the Markov property defining the probability of the current state depends only on the probability of the previous state, was used to illustrate dynamic processes in growth and development of Chinese flowering cabbage.

The aim was to use this model for quantitative analysis of structure-function relationships of Chinese flowering cabbages in which the physiological activity or geometric properties are correlated with their topological structure. 3D visual simulations could additionally be used to study ways to balance vegetative and reproductive growth under greenhouse conditions and open field cultivation.

2. MATERIALS AND METHODS

2.1 Experimental Site

The study was carried out over two Chinese flowering cabbage growing season at experimental farm in Guangzhou, Guangdong Province, China. Topsoil is tropical red loam, and average annual precipitation for this area ranges from 1600mm to 2000 mm. The type and location of the sample on individual plants were recorded each three days within a randomized complete block with 30 replications. Management recommendations for the cultivation of Chinese flowering cabbage, including irrigation, pest and disease control, weeding, and fertilizer application, were the same within each block.

2.2. Plant Material

Chinese flowering cabbage cultivars 'Bilu' were planted using intra-row spacing of 20 cm and inter-row spacing of 25 cm with total plant population density of 200,000 plants/ha.

2.3. Model Description

2.3.1. Topological Model

Topological model, based on probabilities of the occurrence of a branch, provides a quantitative analysis of the growth and development characteristics of Chinese flowering cabbage, which makes it possible to predict the productivity by optimization of the cultural practices.

Each node along the main stem of Chinese flowering cabbage has one leaf bud, one leaf, in which the terminal bud will develop into secondary stem. Hence, a Markov chain with two states can be used to model the growth process of Chinese flowering cabbage. The rank of a node along the stem corresponds to the index of a state in Markov chain. In this context, state 1 represents one secondary stem will develop from the leaf bud, and state 0 represents none leaf bud will develop into one secondary stem attached to the node of the main stem.

Each terminal bud along a secondary stem has form a series of flowers which finally develop into fruits. Hence, a simple Markov model with one state is used to model the fruiting habit of a secondary stem. Similarly, the rank of a node along a secondary stem consists of an index of a state from which Markov chain can be built.

A diagram of a Markov chain with two states is shown in Figure **1**. Initial probability ($p(S_0=i)$) denotes the probability of the first node being a given state, with $i = 0, 1$ where $\sum p(S_0 = i) = 1$. Transition probability (p_{ij}) indicates that the probability of a given state shift from one to another, with $i = 0, 1$ and $j = 0, 1$, where $\sum_i p_{ij} = 1$.

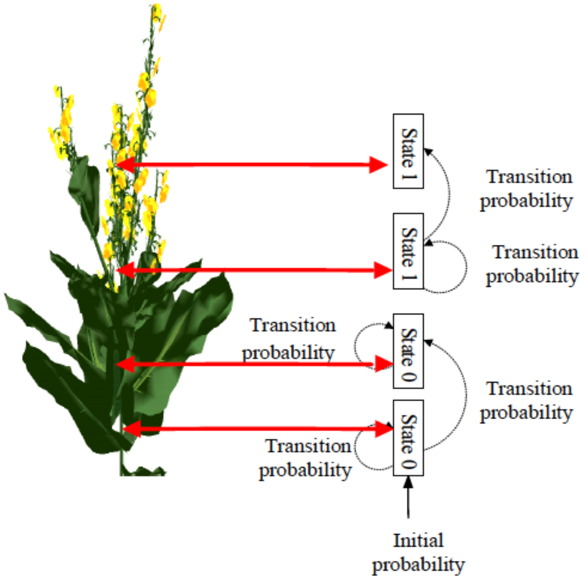

Figure 1: The diagram of a Markov chain with two-states. The transition probability of a given state is represented by the dotted line and the initial probability of a given state by the solid line.

To compute the total number of a given state, occupancy distribution (o_i (n)) is used to count the number of continuous nodes being in the same state, when $I=j$, $o_i(n)=(1-p_{ij})^{n-1}p_{ii}$, where $n = 1.2, \ldots\infty$ and $i=0, 1$.

The initial probability, the transition probability, and the occupancy distribution of a given state in Markov model can be estimated using the Baum–Welch algorithm.

In this study, the binomial distribution is used to depict how often a node '*i*' occurs in '*n*' steps growth, with the probability of occurrence of a single node in one step growth denotes by '*p*' and the probability '*1-p*' of ceases producing the node.

The binomial probability density function for above value and parameters is:

$$P(i,p,n)=\sum\nolimits_{i}^{n} p^{i}(1-p)^{n-i} \quad for\, i=0,1,2,\ldots,n$$

In this regard, terminal bud on a secondary stem can produce only one node per step growth, as is same with that on main stem [8, 20].

2.3.2. Geometrical Model

The geometrical model compute and generate a shape or surface of an organ through built-in functions of random variable [9, 29], as described by Lewis [15, 17].

Bending of an organ, such as leaf, flower and fruit, can be computed according to the beam theory [19].

The initial direction of an organ (initial azimuth) is determined by the geometrical rules of spiral phyllotaxis in nature, which is defined as rotate angle of the organ between two neighboring nodes along the stem. Although each organ of Chinese flowering cabbage locates at a constant divergence angle of 137.5 degrees, the twisting and the sheaths of the nodes have effects on azimuthal shift during the growing period before inflorescence emergence [7].

All organs will vary length-to-width ratios depending on their relative position on main stem [21], which make it easy for users to deal with geometrical attributes in the light of the temporal sequence of morphologic changes.

SIMULATION AND VISUALIZATION

Simulation Tool

The dynamic process of Chinese flowering cabbage can be simulated using PruningSim software [20]. The basic step is the computation of organs (buds, flowers, and fruits), which depend on the state probabilities in Markov chain, *i.e.* the initial probabilities, transition probabilities, and occupancy distributions of state 0 and state 1. For the software usage and detailed simulation process see Xia *et al*. [20].

Figure 2: Simulation of the growth of the nodes. nodes 2, 4, 6, 10, and 12 from the base of main stem are shown in (**A**) to (**F**), respectively.

The Markov chain can capture the change of the organs over time and describe how they connect with each to form the stem. Simulation of Chinese flowering cabbage can execute at a smaller step with one node (see Figure **2**). By contrast, similar dynamic simulation of branching structure of perennial woody plant is not possible due to one or more shoots formation at each step [6, 16, 26, 28, 30, 31].

Figure 3: Simulated leaf positions along main stem over time.

The library of organs was built using 3D max software, designed faithful to the real plant, as described earlier [34]. The gradual elongation of organs over the time was computed using the cubic function.

The inputs of the PruningSim involve of text file that defines the parameters of model and functions and provides some default parameter value. Also, line files that consists of colors of the organs, specific routing of the incoming light, and viewing angle. The 3D visualization results can also be also perceived as single line pictures (see Figure **3**).

Dynamic Simulation of Chinese Flowering Cabbage

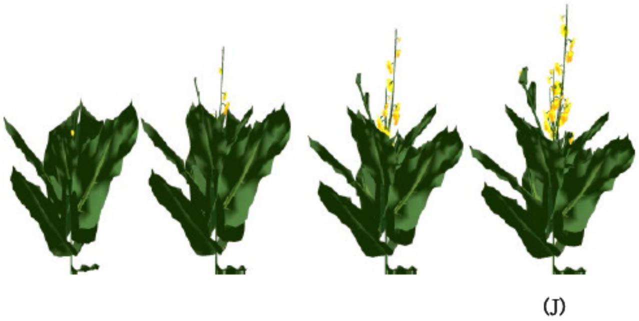

Figure 4: 3D structure of a Chinese flowering cabbage at various stages of development.

The first phase of the simulation, representing a bud break, a leaf and a node formation, is shown in Figure **2**(**A**). Node occurred at about 2 days after the beginning of the bud burst. The terminal bud in main stem is also shown, but it did not sprout in the current step time of the simulation.

The flowering stages of Chinese flowering cabbage are illustrated in Figure **4**. (**G-J**) The values of parameters used in simulations correspond to an internode with its associated organs, rank in order along secondary stem. The simulations reproduce a series of stages of development beginning from the first bud break with one node interval to the cease elongation of secondary stem and fruit formation. The simulations demonstrate that nodes elongate from the base to apex of secondary stem according to the logistic function.

The leaf expands in a similar way as node. The results show rapid growth of the middle leaves, whereas the basal leaves grow more slowly, leading to smaller leaf size. At the second internode, two new leaves occur. By the 12nd node, all leaves unfold along main stem. The upper leaves keep smaller when Chinese flowering cabbage has reached its maximum vegetative height. Nevertheless, upper leaves have not yet reached their final sizes. The results also illustrate that basal leaves have stopped to elongate when upper leaves occur.

The simulations also show regular gradient in leaf orientation, including inclination angle and azimuth. As the stem grows, the leaf inclination angle gradually decreases under the influence of gravity, these patterns are clearly illustrated in Figure **3**, showing different leaf positions along main stem.

Figure 5: Four inflorescence developmental stages along secondary stem of Chinese flowering cabbage. Days 26, 28, 30, and 32 are shown in (**K**) to (**N**), respectively.

Results show terminal flower buds develop into flowers along secondary stem with two-day interval beginning from the 26th days.

DISCUSSIONS AND CONCLUSIONS

A method for visualization of Chinese flowering cabbage dynamic is presented. The method uses a Markov chain with two state to model organogenesis according to the transition probabilities. Based on the principle of botany, such as apical dominance, self-similarity, and phototropism, topological and geometrical attributes of Chinese flowering cabbage is simulated using PruningSim software [34, 35].

The built-in functions in the software describes each organ by introducing a set of mathematical formula, such that complex dynamic can be computed by assigning values to parameters. Topological and geometric model makes it possible to simulate major growth and developments stages of plant from seedling to fruiting faithful to real plant. This may be compared with many previous methods that might require in-depth knowledge of algorithm, programming skills, profound botanical background.

Potential applications of 3D visualization involve Internet of things for sustainable agriculture, agricultural big data [11, 26], teaching internship in agricultural technology [10, 32-34].

In the case of the Chinese flowering cabbage model, 3D visualization made it possible to dynamically simulate in detail how species and varieties, soil, water, and light affect its growth, development and yield. This contrasts the model presented in grain sorghum [1], which only focuses on topological structure, makes it hard to explore structure-function of plant [27, 41]. In addition, at individual or group level, this method provides a tool to test multiple hypotheses which lead to rather different results.

The stochastic model of plant can accelerate large-scale multi-objective optimization, increase computational efficiency, and reduce computational storage. This approach does not necessarily understand the complex principles of botany.

Level of complexity of plant population structure will to some extent lead to some problems about visualization due to the difference between organs and organs. For example, a detailed computation of each leaf is necessary to clarify light interception efficiency of plant population, but it will take a lot of time to compute various variables [24, 37, 40]. The problems can be solved by simplification geometric and/or topological variables.

3D visualization of plant provides knowledge of the structure-function relationship which can be used for applied scientific research and as a method for computational biology [25, 36, 38]. In addition, visualization enhance our understanding of the nature of the population, physiological characteristics, and functional characteristics [35, 39, 42].

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