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A Process Model for Simulation the Growth and Development of Sweet Sorghum

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Abstract: This paper presents a process model of sweet sorghum growth and development which reconstructs realistic 3D images of sweet sorghum with geometric and topological characteristics, and makes it possible to view actual stalk, spike motion from a variety of angles when necessary. Model can also be rotated and the 3D images can be zoomed in and out at a high level of fidelity. They are also used to generate other plant species for use in analyzing the interplay between stochastic and deterministic processes.

Keywords: Sweet sorghum. Stochastic process, Growth and development, Markov model, Computer simulation.

1. INTRODUCTION

3D plant model, visual representation of three-dimensional architecture of plant, can be produced for analytic, scientific and industrial purposes [8, 25]. For example, 3D plant models can be used in computer simulations of landscape evolution [15] and calculations for branching and fruit-setting structures of fruit trees [32].

Computer graphics can create computer-generated imagery (CGI) through 3D rendering algorithm [20]. Some of these plant models focus only on realistic presentation techniques for dynamic simulation rather than on the methods for function approximation, parameter estimation from the field-measured data, which make them difficult to apply to precision agriculture [12].

L-system models can integrate plant parts into reproductive and vegetative structures of whole plants using relatively simple specific algorithms [23,18]. In principle, the rewriting rules of L-systems should make it possible to represent a number of well-defined linear or branched topologies, which could be potentially in general more valuable than simulations. Consequently, it become a powerful computational tool for biological researches.

And in consequence, however, this modeling method is inherently time-consuming and inefficient for describing sophisticated plant architectures under field conditions due to the lack of mathematical tools for analysis of plant development, form and ontogeny. Another challenge comes from the discrepancy between theoretical relationships and experimental results. As a matter of fact, construction of specific, compact sets of data for plant properties still seems quite difficult because of its complexity, heterogeneity and uncertainty [22].

The architectural plant model (AMAP) describes plant architecture through conceptualizing the branching patterns and their growth habits, which integrates physiological processes, botanical laws and field measurements, can contribute to greater efficiency in data analysis, parameterization and simulation [3, 4, 8, 6]. Application of the method was illustrated with example of Austrian black pine plantations. The results showed the ability to simultaneously estimate the topological and geometric parameters describing growth [3]. This method addressed the central problem of plant development: pattern and scale, then it was relatively easy to integrate field-measured values of plant growth parameters. The simulation of plant growth and development relies on the maximum likelihood-based probability analysis of virtual buds. The dynamic state of each bud is represented by numerical magnitude called physiological age, which determines parameter value for each bud in the model. All possible values for physiological ages that make up virtual plant axis is called the reference axis. Regrettably, this approach involves a complexity of concepts and architectures with a wide variability of features and in-built functions in the software [14, 24, 9, 10], which makes it difficult to understand and use in agricultural research, education, and extension without an in-depth background knowledge of software engineering.

This may be compared with analogous approach to measure a large number of data and explore them statistically to uncover numerical relationships [16].

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Unfortunately, the enormous number of plant species with complex branching patterns that need be measured implies inefficiency in data collection, processing, and interpretation.

In recent times, sweet sorghum [*Sorghum bicolor (L.) Moench*] has attracted more interest as an energy crop with high yield potential, water-use efficiency, drought resistance [5, 9, 10]. Compared with several other energy crops such as corn and sugar cane, sweet sorghum is able to adapt to lower level of soil nutrition and obtains a higher biomass productivity [1]. Especially, its juicy stalk contains soluble carbohydrates and sugars which can be completely converted into fuel ethanol with less impact on food and nutrition security than traditional starchy crops such as rice, maize and barley [36].

Nonetheless, the quantitative biomass production of sweet sorghum strongly depends on the cultivars, environmental factors, cultural methods, and management techniques, some aspects of which are still largely unknown [13]. It has become evident that the 3D structure of sweet sorghum strongly affects its physiological function [12], such as the distribution of carbohydrates in root, leaf, stalk, and spike tissues, the light interception properties of leaves and canopies in different plant spacing, and the efficiency of canopy photosynthesis during the life span of leaf.

In the present study, a process model, which describes some statistical properties of topology and geometry, is used to explore the developmental processes of sweet sorghum. The overall objective of this paper is to establish modeling and visualization methods for systematic analysis the architecture of sweet sorghum that use the critical data available to simulate its vegetative and reproductive growth. The present study, as part of a larger study on growth characteristic of plant community, is designed to construct a model of stalk expansion in sweet sorghum. It also provides detailed architectural information for design of bioenergy crop breeding projects.

2. MATERIALS AND METHODS

2.1. Experimental Site

The study was carried out over two successive growing seasons (2015-2016) at experimental ranch in Guangzhou, Guangdong Province, China. Topsoil is red loamy soil, and annual rainfall in this area is from 1600mm to 2000 mm. The observed data on individual plants were collected each ten-day in a randomized complete block with 40 replications. Field management practices, such as irrigation, fertilization, and pesticide application, were the same for all sampling plots.

2.2. Plant Material

Sweet sorghum cultivars 'Dale' were planted at a density of 95238 plants/ha with a within-row spacing of 15cm and between-row spacing of 70cm.

2.2. Model Description

2.2.1. Topological Model

Topological model, based on probabilities of the occurrence of an internode, provides a quantitative method to explore the growth and development characteristics of sweet sorghum under different environmental conditions, which makes it possible to evaluate the cultural practices that optimize the productivity.

Each internode along the stalk of sweet sorghum has one bud (leaf bud or blossom bud), one leaf and one node, in which the terminal blossom bud will develop into a spike. Hence, Markov chain model with two states is used to describe quantitatively the growth process of sweet sorghum. The rank of an internode along the stalk corresponds to the index of a state in Markov chain model. In this context, state 1 represents one blossom bud will form a spike attached to the internode of the stalk, and state 0 represents one leaf bud will develop into one leaf attached to the internode of the stalk.

2.3. Model Description

Each internode along the stalk of sweet sorghum has one bud (leaf bud or blossom bud), one leaf and one node, in which the terminal blossom bud will develop into a spike. Hence, Markov chain model with two states is used to describe the stalk expansion. The rank of a node along the stalk consists of an index of a state from which Markov chain can be built. In this context, state 0 represents zero blossom bud borne on a node, state 1 represents one blossom bud borne on a node.

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

To compute the total number of state, occupancy distribution (o_i (n)) is used to sum the number of successive internodes being in the same state, when $i = j, o_i(n) = (1-p_{ii})^{n-1} p_{ii}$, *where* $n = 1.2,...\infty$ *and* $i = 0,1$.

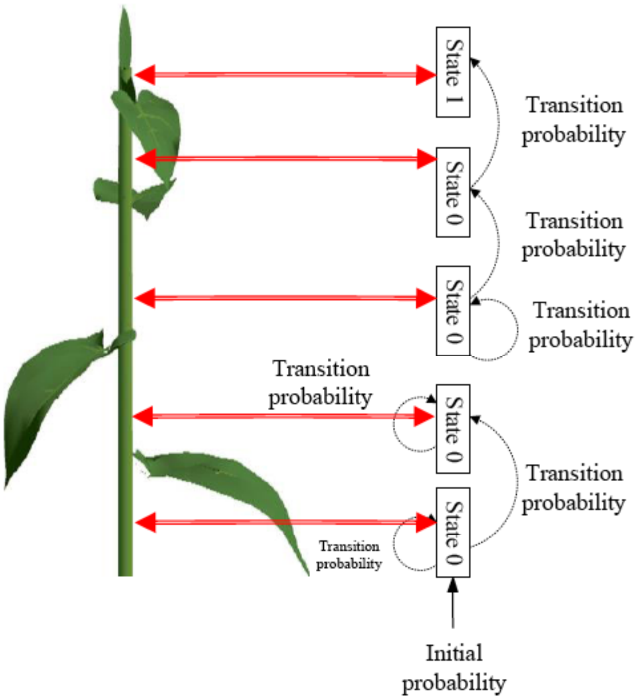

Figure 1: Schematic structure of the Markov chain with two-state. The transition probability of a state is represented by the broken line and the initial probability of a state by the continuous line.

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 count how often an internode 'i' occurs in 'n' growth steps, with the probability of occurrence of a single internode in a single step denoted by 'p' and the probability '$1-p$' of ceased producing the internode.

The following formula is the binomial probability density function:

$$P(i,p,n) = \sum_i^n p^i (1-p)^{n-i} \text{ for } i = 0,1,2,...,n$$

Each parameter value may change associated with structural changes of each stalk of sweet sorghum. In this regard, terminal bud on the stalk can produce only one internode per growth step, as is different with that on the annual shoot of fruit tree which produce tens of internodes [20].

2.2.2. Geometrical Model

The presented geometrical model is based on the recently developed software tool [20], which makes use of built-in functions of random variable to compute and generate a shape or surface of an organ faithful to its real geometrical structure [29].

Each organ placed in 3D space and its scaling attributes is computed by using similar methods as described by Lewis [17]. For example, the inclination angle of the leaf tip is given as functions of curvilinear distance from the leaf base to the leaf tip, where the angular value may vary between zero degrees (which is 0 at the leaf base, also called leaf insertion angle) and 180 degrees (which is 180 at the leaf tip). Bending of an organ can be modelled according to the beam theory [19].

The initial direction of a leaf (initial leaf azimuth) is determined based on the geometrical rules of spiral phyllotaxis in nature, which is defined as rotate angle of the leaf between two adjoining internodes along the stalk. Although each leaf of sweet sorghum stands at a constant divergence angle of 137.5 degrees to the previous or next leaf, the twisting of the internodes, the sheaths and the nodes have effects on azimuthal shift during the growing period before spike emergence [7].

All the internodes together with their component have varying length-to-width ratios depending on their relative position on the stalk [21].

In the geometric model, parameters of the organs can be indexed to their position on the stalk, which make them easy for users to deal with geometry in terms of the temporal sequence of morphologic changes.

SIMULATION AND VISUALIZATION

Simulation Tool

The growth and development process of sweet sorghum can be simulated by the pruningsim software [20]. The basic step for simulation is the output of internode and its associated organs, which depends 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 modularization and detailed interfaces of software tool see Xia *et al*. [20].

The Markov chain model captures the change of the organ over time and defines how they join together to construct the structure of stalk. Simulation of sweet sorghum can proceed at a smaller time step with only one internode formation. By contrast, similar dynamic simulation of branching structure of fruit tree is not possible due to one or more shoots at each time step [30, 31].

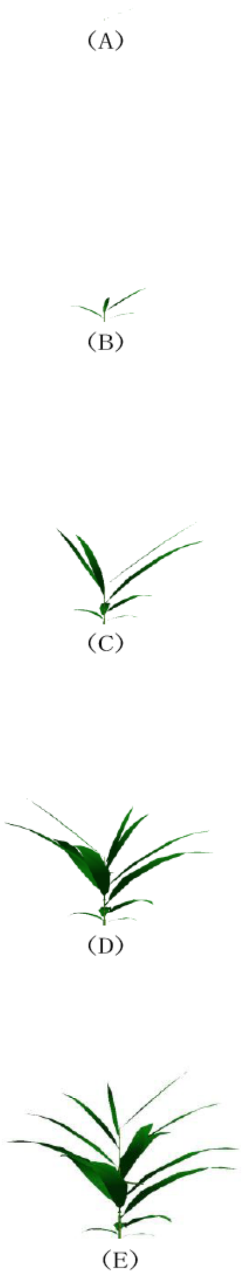

Figure 2: Simulation of internode growth. Internodes 2, 6, 10, 14, and 16, and 28 from the basal bud emergence are shown in (**a**) to (**e**), respectively.

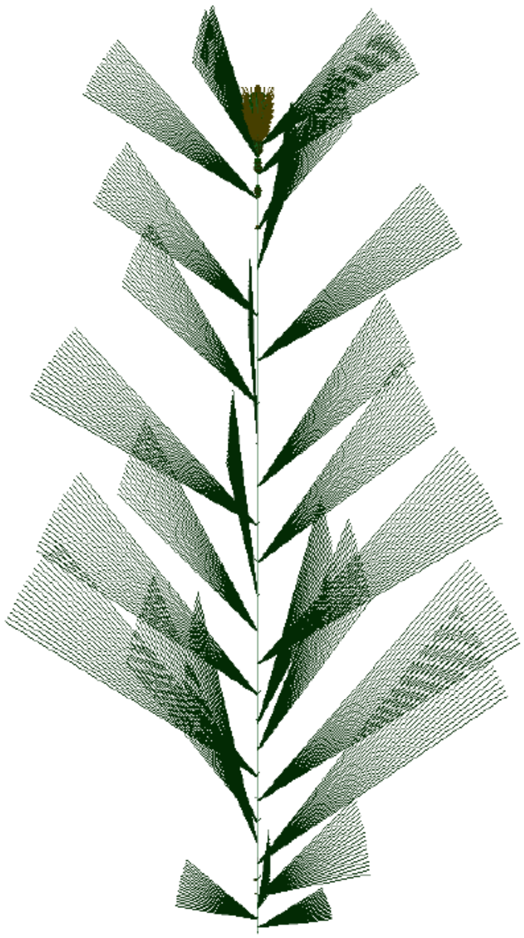

Figure 3: Simulated progression of leaf positions of the stalk over time.

The shapes of organs are reconstructed using 3D max software, designed according to realism, as described earlier [34]. The gradual elongation of organs over the growth period is captured by means of the cubic function.

The input to the pruningsim consists of documents files that define the parameters of model and built-in functions, and provide some default values necessary to generate 3D pictures. These comprise colors of the organs, specific routing of the incoming light, and viewing angle. A plugin for pruningsim can help to select the colors on the interactive palette. The simulation results can also be also represented as traditional single line drawings (see Figure **3**).

Dynamic Simulation of the Stalk of Sweet Sorghum

The startup phase of the simulation, representing a bud break and an internode formation, is shown in Figure **4**(**1**). Internode occurred at about 3 to 5 days after the beginning of the bud burst. The uppermost

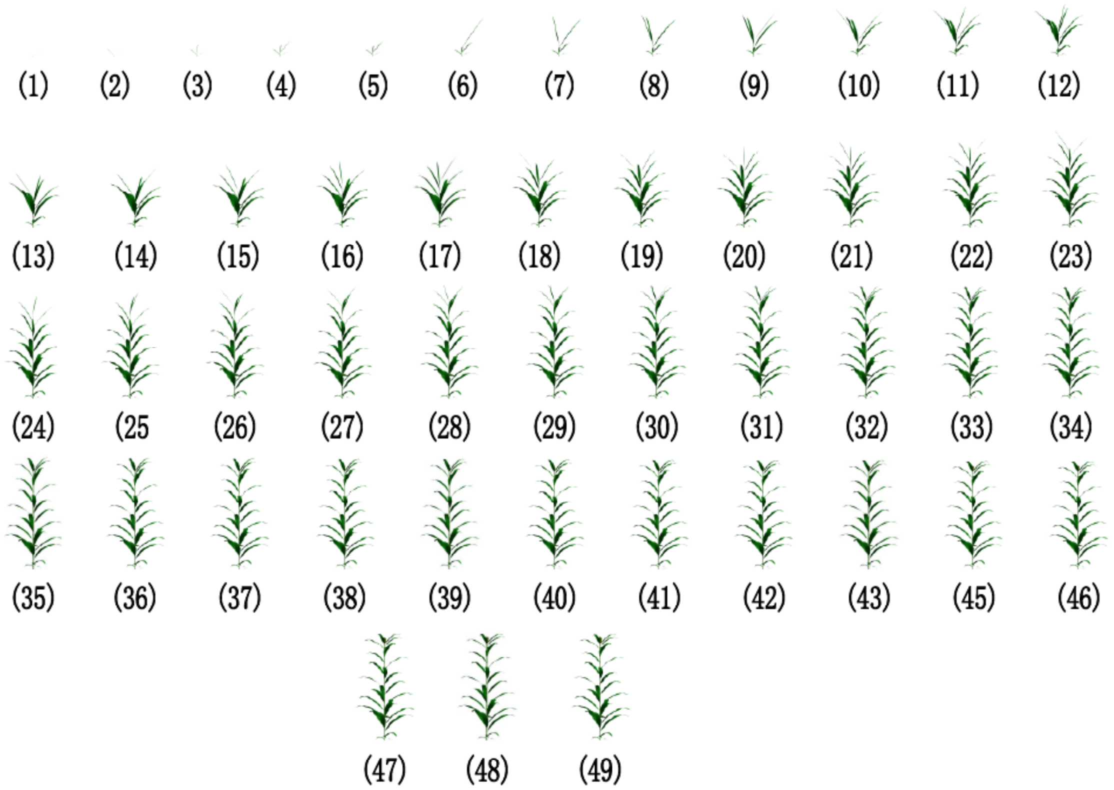

Figure 4: Three-dimensional structure of an Sweet sorghum at various stages of development.

bud in the internode of the stalk is also shown, but it did not sprout in the current time step of the simulation.

The consecutive developmental stages of sweet sorghum are illustrated in Figure **4** (**2-30**) the values of parameters used in simulations correspond to an internode with its associated organs, arrange in order along the stalk. The images reproduce a series of stages of vegetative growth beginning from the first bud break with one internode interval to the halt of the stalk expansion and formation of the terminal flower bud. The simulations demonstrate convincingly that internodes develop in order from the base to apex of the stalk. In the case of internodes, this tendency can be described using the logistic function.

The leaf expansion has a similar acropetal pattern. The simulation results reveal rapid growth of the proximal leaves, whereas the distal leaves grow more slowly, resulting in a smaller leaf size. At the second internode, two new leaves emerge. By the 31st internode, all leaves unfold on the stalk. The upper leaves remain small until the 38th internode when sweet sorghum has reached its maximum height. Nevertheless, all leaves have not yet reached their final sizes, in which the upper leaves then grow rapidly after this time and at last reach a maximum size. The simulation also illustrates that basal leaves have stopped to expand when apex internode occurs.

The image also shows the gradual change in leaf orientation, such as leaf inclination angle and leaf azimuth. As the stalk grows, the leaf inclination angle gradually decreases due to gravity, these dynamic characteristics are clearly illustrated in Figure **3**, showing a sequence of leaf positions during vegetative growth stage.

Morphological Variation of the Spike of the Sweet Sorghum

Figure **5** shows major spike developmental stages in sweet sorghum. Images represent five phases of expansion at 4-internode intervals beginning from the 32nd internodes with a terminal flower bud develop into a spike. Internodes 32, 36, 40, 44, and 48 from the basal bud emergence are shown in (A) to (E), respectively.

DISCUSSIONS AND CONCLUSIONS

A method for modeling and visualization of sweet sorghum growth is presented. The method uses a Markov chain to assess organogenesis according to the transition probabilities for each state representing

Figure 5: Simulation of the expansion of a spike from terminal flower bud.

plant organ transitioning to any other state (including itself). Based on the concept of morphogenesis such as apical growth, branching, fruiting, self-pruning, reiteration or ageing, plant topological and geometrical structure is simulated using pruningsim software.

The embedded architectural model in the pruningsim software describes each plant component (or group of components) by introducing a set of growth functions that have been already chosen and fixed to capture the growth and development processes, such that complex plant architectures can be generated simply by assigning values to variables. The integration of topology and geometry makes it possible to simulate the main morphological stages of plant from seedling emergence until ripening period without sacrificing botanical reality. This may be compared with many previous models that might require in-depth knowledge of algorithmic programming and technique for deriving the set of rewrite rules or productions.

Potential applications of integrating simulation and 3D visualization include intelligent systems for sustainable agriculture and environment as well as tools for scientific computing [11, 26], teaching theoretical concepts in agricultural management practices [34], and training [32, 33].

In the case of the sweet sorghum growth model, realistic simulation and 3D visualization made it possible to dynamically analyze in detail how the genetic, nutritional, and environmental factors affect sweet sorghum growth, development and yield. This contrasts the approach presented in grain sorghum growth model [2], which only focuses on capturing one aspect of its morphological architecture, making it difficult to understand the physical and physiological characteristics in complex processes of light interception [27], photosynthesis, respiration, and water use.

In addition to interactive simulation, at individual plant and stand scale it is possible to test different hypotheses by and analyzing the integrated morphological and physiological responses to a stressful virtual situation.

The stochastic process model of sweet sorghum relies on a set of techniques that aim to simplify calculation and simulation to reduce parameter uncertainty. These approaches do not necessarily explore the underlying mechanisms in morphogenetic processes.

Structural complexity of plant population will to some extent lead to a lot of additional challenges of simulation due to the uniqueness of each individual plant. For example, for calculation of light interception efficiency of plant population, a detailed representation of each leaf will take considerable computational time because of large number of variables [24]. A structural simplification method of plant population by its geometric and/or topological variables may address the issue.

3D model may improve our understanding of plant architectural characteristics and can be used for educational purposes and as a method for non-graphical computer calculations [25]. Real-time interactive visualization for realistic data-specific plant simulation provides an opportunity for learning about the life cycle of a plant, environmental factors that influence vegetative and reproductive growth and what can be done to promote optimum conditions for cultivation during the stage of growth and development, thus assisting in determination of breeding strategies for plants.

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