Simulation and Quantitative Analysis of Branching Patterns of the Plum Tree

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Abstract: *Background and Aims:* Pruning fruit tree is undoubtedly a critical cultural practice which leads to sustainable production along with profitability of the trees. Several limitations of classic approaches pertaining to studying pruning techniques based mostly on fruit yields and quality evaluations have kept us from thoroughly understanding the growth habits of branches under field conditions. A simulation model of branching patterns of the plum tree (*Prunus salicina* cv. Sanhua) introduced in this paper enables both non-professionals and professionals to better understand and predict pruning effects on branching pattern and fruiting habit of the trees. The visual comparison of branching and fruiting characteristic of the prunedparent shootprovides immediate feedback on different pruning intensities at the level of shoots.

Methods: Semi-Markov chains were built with diverse initial probabilities, transition probabilities and occupancy distributions to describe the number of occurrence of girl shoots along the pruned parent shoot. Branching structures were reconstructed using AmapSim computer software with different shoot types, considering topological and geometrical functions.

Key Results: The results demonstrated different branching zones in the pruned parent shoot were found in the same order. Moderate heading back and slight heading back parent shoots differed in short shoot position. Of all pruning intensities, the branching zone in severe heading back parent shoots was shorter than the sylleptic branching zone. The three-dimensional reconstruction images of pruned parent shoots displayed illustrative examples to elucidate proper pruning technique among three pruning intensities.

Conclusions: Severe heading back parent shoot had a strong branching capability. In comparison with moderate heading back, slight heading back parent shoot had a higher proportion of fruiting zones, therefore the latter is usually considered balancing vegetative and reproductive growth in the conventional pruning of plum trees.

The stochastic model could serve as a feasibility groundwork against which quantitative differences in branching structures of prune parent shoot under different pruning systems can be compared.

Keywords: Plum tree, *Prunus salicina*, Virtual pruning, Orchard management, Shoot.

INTRODUCTION

Pruning fruit tree is one of important cultural practices which contributes substantially to enhance fruit yield and improve quality [1]. Through proper pruning, the form and bearing habit of fruit trees is regulated, thereby more and better fruit crop is obtained at less cost and in a much longer time than is possible without pruning. Teaching pruning techniques with a slide show in the classroom are a challenging primarily because of time delay between pruning and sprouting of the pruned tree. This specific time delay makes it hard for teachers, whether or not precisely, to make instructional evaluation.

Some limitations in classic methods of studying pruning, based mostly on fruit yield and quality evaluations, have prevented us from thoroughly understanding the dynamic growth of trees under field conditions [2]. Indeed, precise information associated with branching patterns of pruned shoots can be obtained by digitizing method in an orchard [3], however, it is time consuming and labor intensive. Although encouraging advances in statistical models that represent branching structures have already been reported for fruit trees, such as apple [4], grape [5], kiwifruit [6], and apricot [7], unfortunately, these reports have merely concerned on modeling natural-form fruit trees without pruning. Little information on the branching pattern of plum trees affected by pruning has been released [8-10].

Three dimensional models can certainly illustrate the plant with startling reality using effective visual modeling tools, as Light Wave 3D, 3DS MAX, and AutoCAD, yet most of these modeling methods emphasis on visual interest than botanical and agronomic consideration.

A few structural-functional modeling methods, such as LIGNUM [11], L-studio [12] and L-Py [8], offer equivalent models depending on rewriting grammar in which the user needs to create the rule set that describe plant structure, consisting of both topological parameters and geometric parameters [13], however, it is undoubtedly difficulty for users to enter into plant

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modeling lack specific background knowledge of mathematics, botany, computer graphics, and computer programming skills.

In comparison with analogous modeling tools as DigiPlante and AmapPara [14] having preset model parameters, AmapSim utilizes embedded plant model parameters together with external functioning models to simulate the growth of plant in terms of both botanical terms and agronomic traits.

The main works in this report are to build a model and to visualize pruning of plum tree using AmapSim. The integrated model will be carefully validated and evaluated, then, is used to analyze pruning effect of three pruning intensities on branching patterns of parent shoots. Furthermore, how to maintain tree productivity and sustainability by proper pruning was discussed.

MATERIAL AND MEHTODS

Uniform six-year-old mature plum trees (*Prunus salicina Lindl.,*'Sanhua') grown in Yangjiang Commercial Orchard, Guangdong Province, China, were chosen for this study. 40 randomly selected trees were measured. The shoots, which had lengthened in the last growing season, were referred to as parent shoots. Four main types of current-year shoots could be identified according to their length and structures: (i) latent bud (ii) proleptic short shoot (<15 cm in length), (iii) nonsylleptic long shoot (>15 cm), and (iv) sylleptic long shoot.

The parent shoots were pruned to three to twelve retained nodes during dormant winter pruning. They were called 3-node-left heading back (*3nhb*), 4-node-left heading back (*4nhb*)…, and 12-node-left heading back (*12nhb*). "*4nhb*" and less represent severe heading back, "*5nhb*" to "*9nhb*" represent moderate heading back, and "*10nhb*" and more represent slight heading back.

The number, types, location, and length of lateral shoots developing from the retained buds of parent shoots were recorded. In this study, the nodes of each parent shoot were numbered starting from the proximal nodes.

Hidden Semi-Markov Model

Each lateral shoot developing from the pruned parent shoots was a discrete event with specific state. Thus, branching structure can be modeled using the theory of stochastic process [15].

A given type of lateral shoot was represented by a symbol: 0 for a latent bud, 1 for a proleptic short shoot, 2 for a nonsylleptic long shoot, and 3 for a sylleptic long shoot. The pruned parent shoot consisted of a string of branching zones. Each zone, representing a state in Markov chain, is symbolized by the type of lateral shoot: zone 1 represents non-branching zone, zone 2 represents proleptic branching zone (including possible lateral shoot type 0, 1,and 2); zone 3 for sylleptic branching zone (including possible lateral shoot type 0, 1, 2 and 3). The zone 2 and zone 3 could be discerned by occurrence of sylleptic long shoot. In this study, we used hidden semi-Markov model with three states to model branching pattern of pruned parent shoots.

A *j*-state hidden semi-Markov chain is defined by the following parameters[15]:

The initial probability (π_k) is the probability of the first occurrence branching zone *k* along the pruned parent shoot,

$$\pi_k = P(S_1 = k) \text{ with } k = 1,...,J \tag{1}$$

where $\sum_{k=1}^{J} \pi_k = 1$

The transition probability (p_{ik}) is the probability of transferring for branching zone *i* to branching zone *k*,

$$p_{ik} = P(S_n = k / S_{n-1} = i), \text{ with } i = 1,\dots,J-1 \text{ and } k = 1,\dots,J \tag{2}$$

where $\forall_i \in \{1,...,J-1\}, \sum_{k=1}^{J} p_{ik} = 1$

The occupancy distribution ($d_k(u)$) is the distribution of branching zone *k* occupying different numbers of nodes,

$$d_k(u) = P\begin{pmatrix} S_{n+u+1} \neq k, S_{n+u-v} = k, \\ v = 1,...,u-1 / S_{n+1} = k, S_n \neq k \end{pmatrix}, u = 1,2,. \tag{3}$$

The first occurrence distribution ($\alpha_{k,y}(n)$) is the first occurrence of a given lateral shoot type *y* in branching zone *k* measured in number of nodes,

$$\alpha_{k,y}(n) = P\begin{pmatrix} S_{n+1} \neq k, S_n = k, \\ X_{n-v} \neq y, v = 1,...,n \end{pmatrix} \tag{4}$$

The recurrence distribution ($\beta_{k,y}(v)$) is the interval between occurrence and reoccurrence of a given lateral shoot type *y* in branching zone *k* measured in number of nodes,

$$\beta_{k,y}(v) = P\begin{pmatrix} S_{n+u} \\ = k, S_{n+u-w} \neq k, X_{n+v-w} \neq y, \\ w = 1,...,v-1 / S_n = k, X_n = y \end{pmatrix}, v = 1,2,... \tag{5}$$

The sojourn distribution ($\gamma_{k,y}(v)$) is the successive occurrence of a given lateral shoot type *y* in a given branching zone *k* measured in number of nodes,

$$\gamma_{k,y}(v) = P\begin{pmatrix} S_{n+u+1} \neq k, S_{n+u-v} = k, \\ X_{n+v-w} = y, v = 1,\ldots,u-1, \\ w = 1,\ldots,v-1 / S_{n+1} = k, \\ S_n \neq k, X_{n+1} = y, X_n \neq y \end{pmatrix}, u = 1,2,\ldots \qquad (6)$$

The parameters of mode1s were estimated by the STAT module of Matlab® software.

3D Reconstruction of the Pruned Parent Shoot

The distribution of lateral shoots along the pruned parent shoot can be visualized as three-dimensional images by using the AmapSim growth generator.

AmapSim is built with structural model, C/C++ language that reconstructs a 3D architecture of plant with estimating the parameter values based on measured data on real plants. AmapSim is an Open Source application available for Windows, Linux, and UNIX operating system, written by Barczi *et al*. [16]. The simulation process depends on the fate of virtual buds with physiological age along the reference axis (see Figure **1**). The reference axis is the theoretical axis considering possible growth dynamics of virtual buds in a pruned parent shoot, whose branching law (*i.e*. the probabilities of virtual buds growing into short, long, sylleptic shoots, and so on) is modeled using semi-Markov chain.

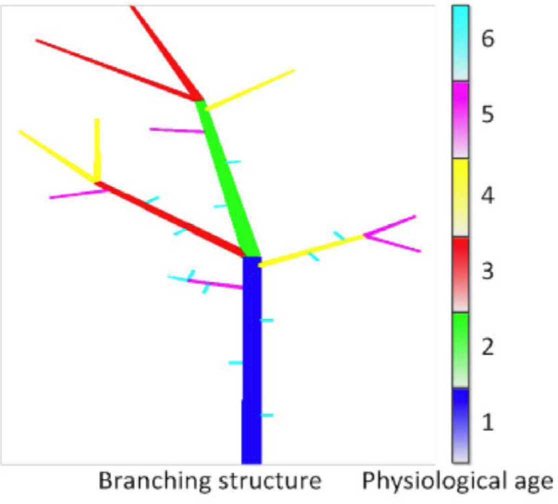

Figure 1: Schematic diagram of the reference axis.

Weillustrate the fundamental concepts and steps to the actual simulation process,for a more detailed information abut how to use AmapSim growth generator, see Xia *et al*. [17].

RESULTS

Quantitative analysis branching patterns of the parent shoots for "7nhb"

In what follows, anexhaustive explanation for "*7nhb*" was given to quantitative analysis of branching patterns, which was then used as a reference for evaluating other pruning intensities.

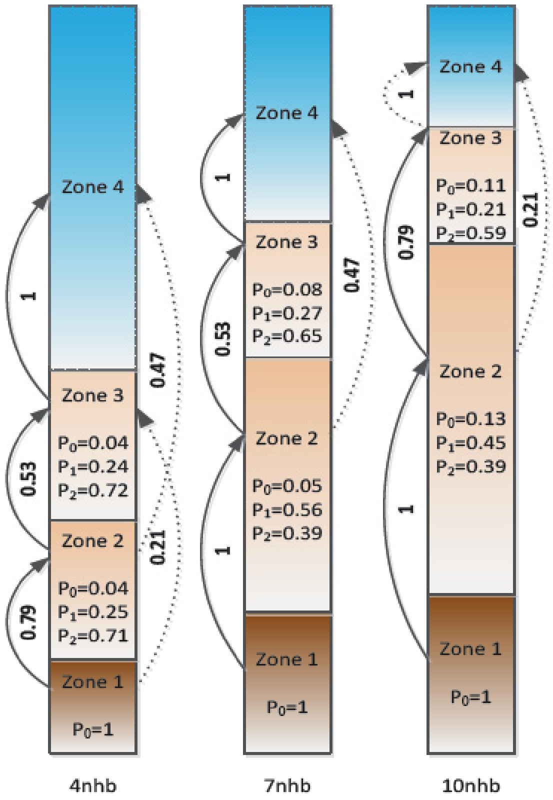

Figure 2: Hidden semi-Markov models under to different pruning intensities. The branching zones are represented by different boxes from zone 1 to zone 4. The observed probabilities of lateral shoots are given within the zone boxes (except for base and upper zones where latent buds and removed parts of the parent shoot present, respectively), the possible state transitions are represented by arrows (the associated transition probabilities are labelled).

Branching zones along the parent shoots for "*7nhb*" can be divided into three branching zones (removed zone being excluded) as follows (Figure **2**): The basal zone, located on the first 1.0 node, corresponded to empty nodes, the middle zone was occupied mainly by short and nonsylleptic long shoots, mixed with latent buds. It is to be noted that most of fruits located within this branching zone in pruned parent shoots. The upper zone corresponded to sylleptic long shoots, located on the last 1.1 nodes from the base and was mixed with a few latent buds, short, and nonsylleptic long shoots.

Table 1: Main Characteristic on the Branching Zone of Parent Shoots

Pruning intensities	Mean number of occurrence of lateral shoot				Mean number of first occurrence of lateral shoot		
	0	1	2	3	1	2	3
3nhb	0	0.4	1.6	1	0.1	1.4	1.5
4nhb	0.2	0.8	2.1	0.9	0.3	2	2.1
5nhb	0.5	1.8	1.7	1	0.9	2.4	3.1
6nhb	0.4	2.3	2.1	1.2	1.1	3.2	3.4
7nhb	0.8	2.7	2.4	1.1	2.5	3.2	3.7
8nhb	0.6	3.4	2.7	1.3	2.4	4	4.1
9nhb	1.3	3.1	3.3	1.3	1.9	4.5	4.8
10nhb	2.1	3.5	2.9	1.5	3.4	4.9	6.2
11nhb	2.7	3.7	3.2	1.4	3.4	5.1	7.7
12nhb	3.1	3.9	3.3	1.7	3.1	6.3	8.1

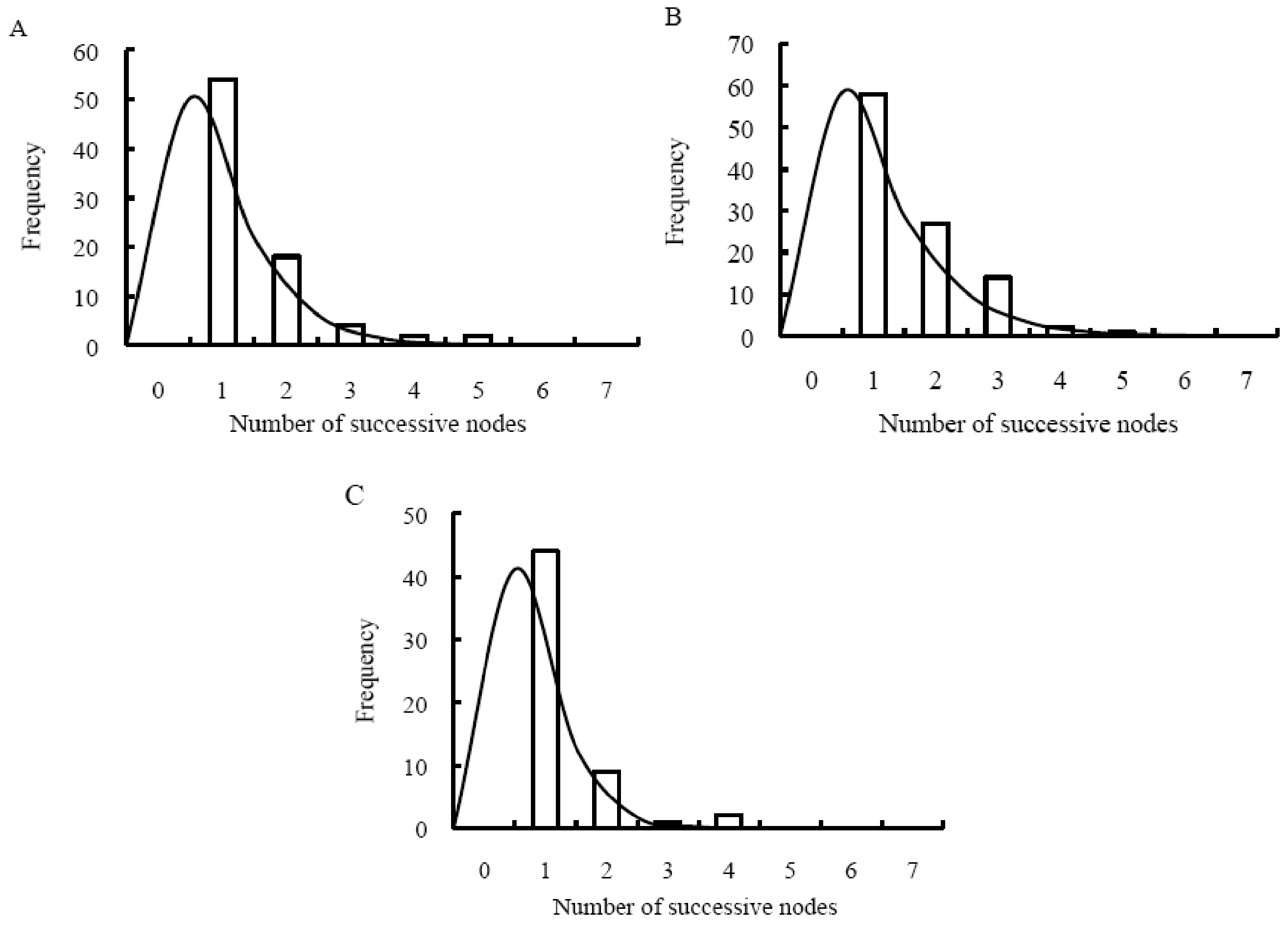

Figure 3: Sojourn-nodes distribution of lateral shoots on “7nhb” parent shoot. **A, B** and **C** correspond to short shoot, nonsylleptic long shoot and sylleptic long shoot, respectively. The observed data are represented by the histogram and the theoretical distribution by the continuous line.

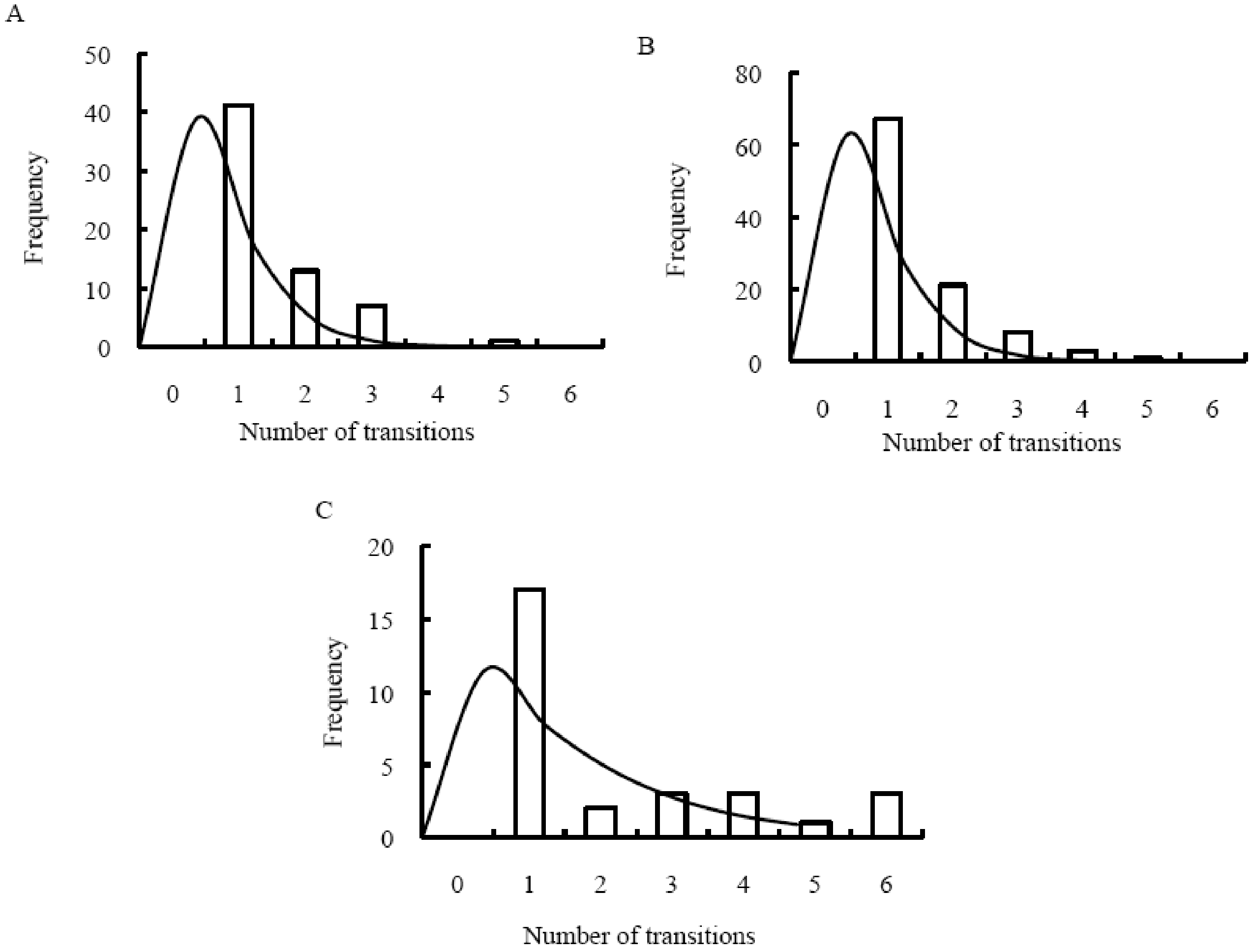

Figure 4: Recurrence-nodes distribution of lateral shoots on "7nhb" parent shoot. **A, B** and **C** correspond to short shoot, nonsylleptic long shoot and sylleptic long shoot, respectively. The observed data are represented by the histogram and the theoretical distribution by the continuous line.

The characteristics of four types of lateral shoots extracted from observed data were shown in Table **1**. Proportion of lateral shoots showed that the number of proleptic short shoots was different in three branching zones of the pruned parent shoot. Probability distribution illustrated the interval of proleptic short shoots since the most frequent number of successive and transition node was one (Figures **3** and **4**).

When fourtypes of lateral shoots were considered, 86% of lateral buds developed along the parent shoots for "*7nhb*". Of the sprouting buds, approx. 45%, 35%, 13% developed into proleptic short shoots, nonsylleptic long shoots, and sylleptic long shoots, respectively. The number of two types of lateral shoots were approximately equal: the latent buds and the sylleptic long shoots was approx. 1.0 and 1.1, respectively. Nonsylleptic long shoots and sylleptic long shoots occurred alone in the same way as proleptic short shoots (Figures **3** and **4**).

The branching structure of the pruned parent shoot was viewed as a series of zones in which the lateral types remained the same, but varied with zones. To represent it, a hidden semi-Markov chain model was built (Figure **2**). In this model, basal non-branching zone constituted approx. 14% of the pruned parent shoots. The middle and upper branching zones might comprise latent buds, proleptic short shoots, nonsylleptic long shoots and sylleptic long shoots, as previously described. The zone lengths were expressed in terms of occupancy distributions of HsMM, which were all binomial distributions. The combination of lateral shoots located in the same zone showed in the observation distributions (Figure **2**).

The validation of model was conducted by checking the conformity between observed data and theoretical values expected under the model (Figure **5**).

Comparison of branching pattern sunder three pruning intensities

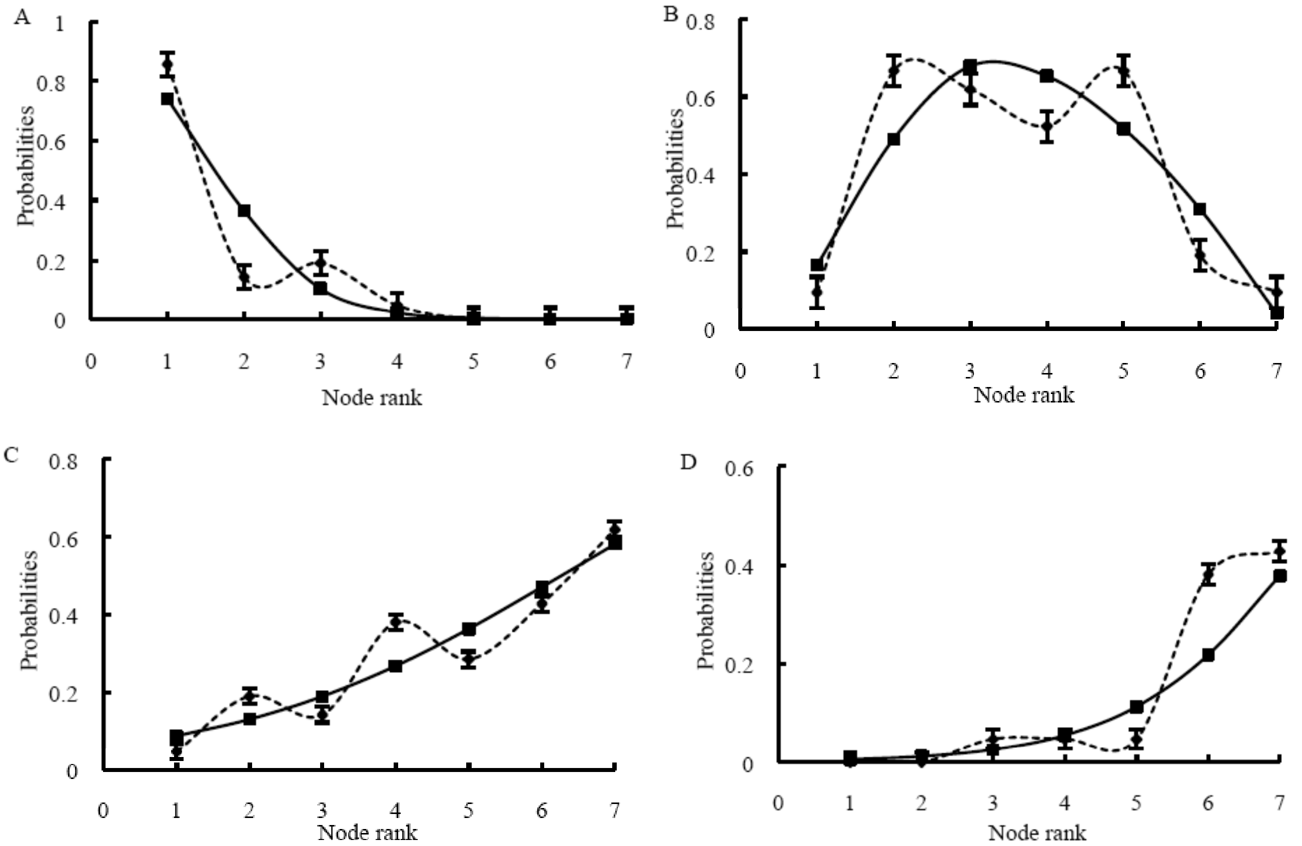

Figure 5: Comparison between observed and theoretical probabilities of lateral shoots according to the node rank on "7nhb" parent shoot. **A, B, C** and **D** correspond to latent bud, short shoot, nonsylleptic long shoot and sylleptic long shoot, respectively. Dotted lines represent probabilities estimated from observed data, and solid lines represent theoretical probabilities calculated by the hidden semi-Markov chain model.

Table 2: Initial Probability of Hidden Semi-Markov Models Corresponding to Different Pruning Intensities

Branching zone	Initial probability									
	3nhb	4nhb	5nhb	6nhb	7nhb	8nhb	9nhb	10nhb	11nhb	12nhb
1	0.09	0.14	0.64	0.79	0.81	0.65	0.79	0.82	0.91	0.97
2	0.81	0.77	0.36	0.21	0.19	0.35	0.21	0.18	0.09	0.03
3	0.1	0.09	0	0	0	0	0	0	0	0

Figure **2** demonstrated that all of branching zones in "*4nhb*" and "*10nhb*" parent shoots were located in the same order as previously mentioned for "*7nhb*". Like moderate pruning intensity, slight and severe pruning intensity exhibited high transition probabilities, especially in the middle and basal branching zone, however, the initiation probabilities of different pruning intensities were very inconsistent (Table **2**), especially: the initiation probability of three branching zones for "*3nhb*" were 0.09, 0.81, 0.10, while corresponding to "*7nhb*" were 0.81, 0.19, 0.00, respectively.

Nonsylleptic long shoots and sylleptic long shoots along the parent shoots for "*12nhb*" were isolated in the same manner as proleptic short shoots (Figures **6** and **7**.). The numbers of latent budsrose dramatically. These results indicated the effect of different pruning intensities on lateral distribution along the parent shoots: severe heading back activated vegetative growth, while slight heading back inhibited bud sprouting at the basal.

Moderate heading back and slight heading back differed in proleptic short shoot location, which was

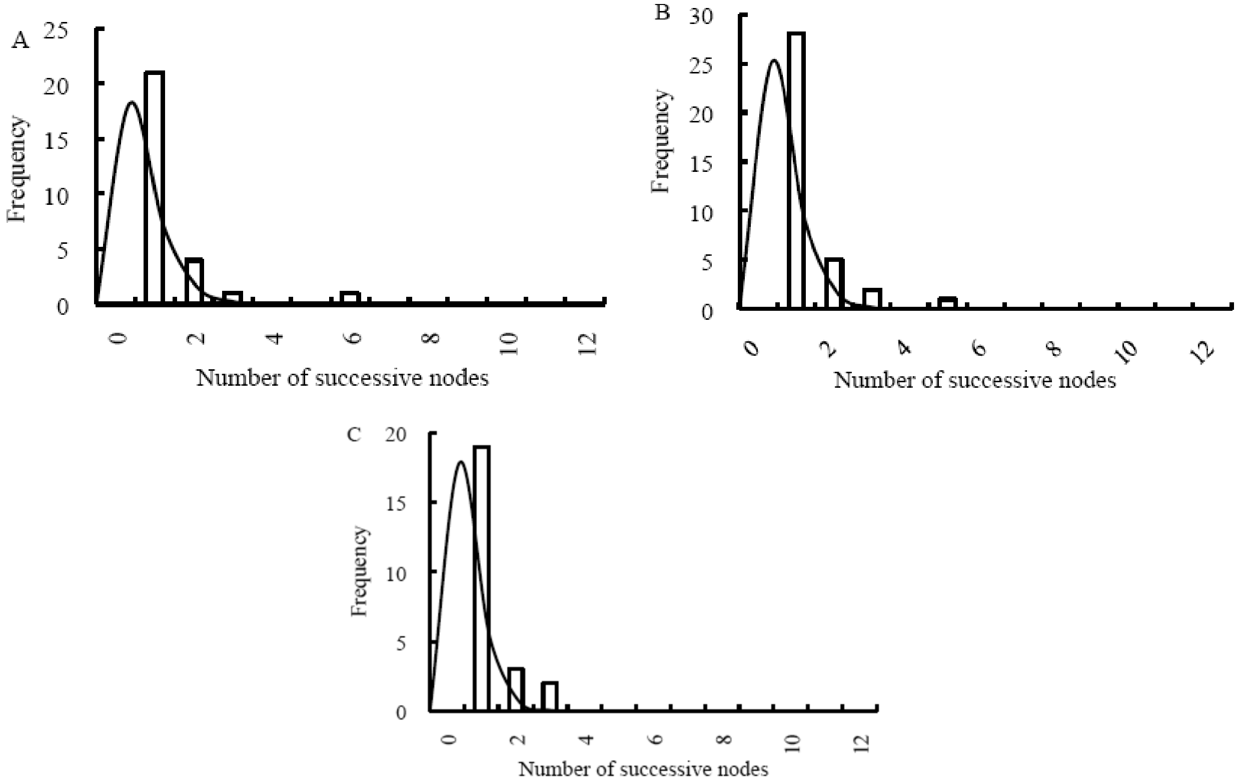

Figure 6: Sojourn-nodes distribution of lateral shoots on "12nhb" parent shoot. **A, B** and **C** correspond to short shoot, nonsylleptic long shoot and sylleptic long shoot, respectively. The observed data are represented by the histogram and the theoretical distribution by the continuous line.

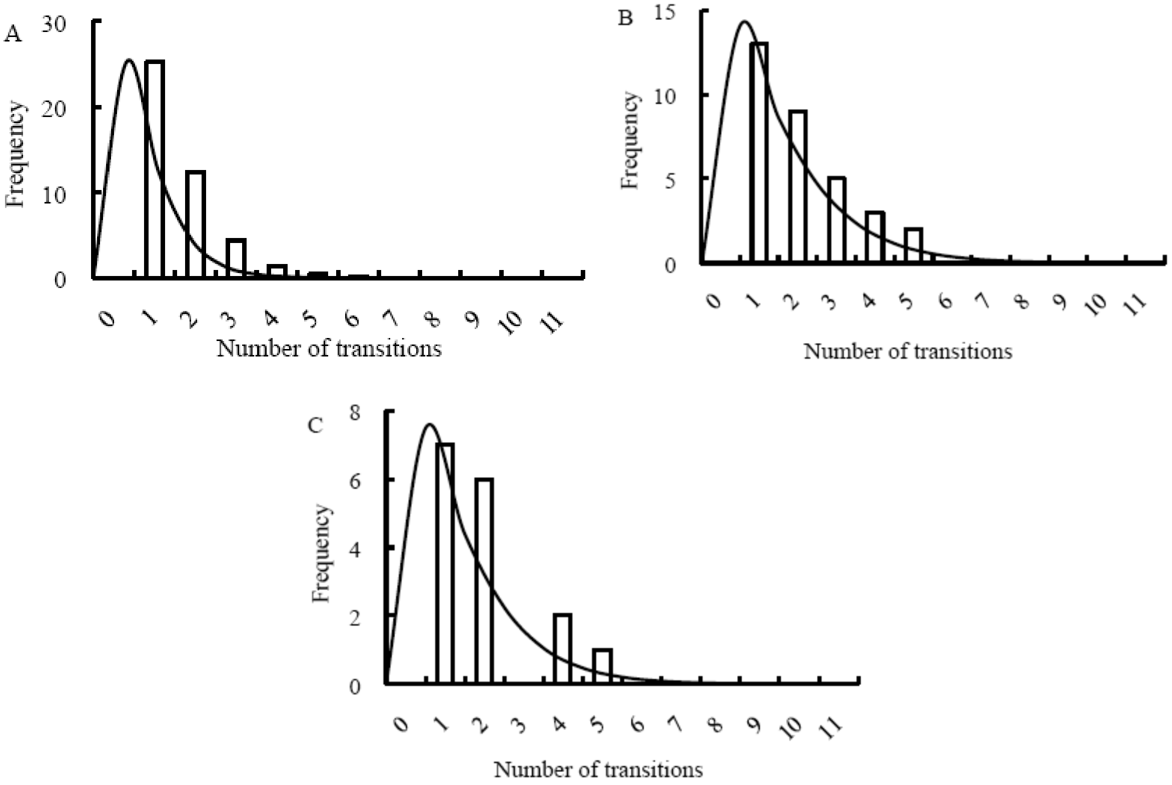

Figure 7: Recurrence-nodes distribution of lateral shoots on "12nhb" parent shoot. **A, B** and **C** correspond to short shoot, nonsylleptic long shoot and sylleptic long shoot, respectively. The observed data are represented by the histogram and the theoretical distribution by the continuous line.

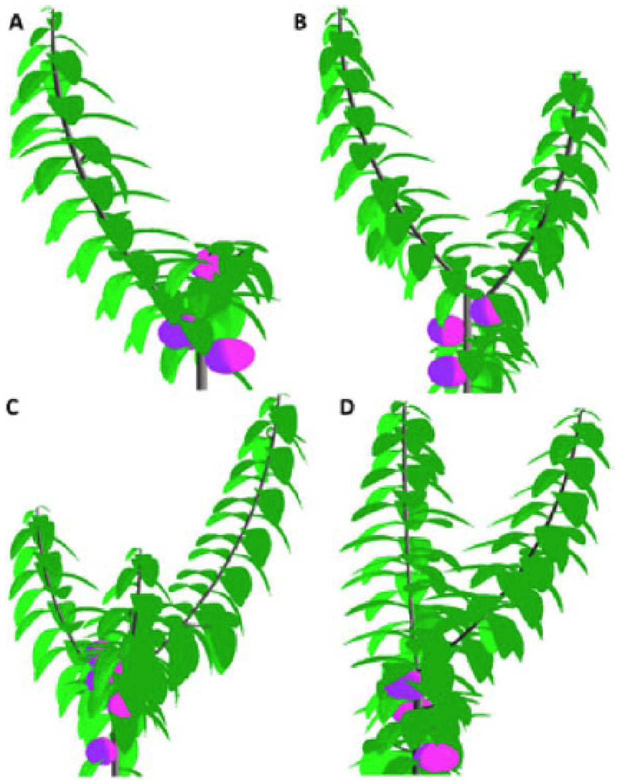

Figure 8: Some examples of simulated architectures. **A, B C** and **D** correspond to “4nhb”, “7nhb”, “10nhb” and “12nhb”, respectively.

mainly located in at three node ranks and four node ranks, respectively. “*3nhb*” was characterized by the absence of non-branching zone defined by latent buds in more than 95% of parent shoots. The number of latent buds in basal non-branching zones were less than middle and upper (and sylleptic) branching zone for “*4nhb*” to “*9nhb*”, while it were more for “*10nhb*” to “*12nhb*” (Table **1**). “*4nhb*” to “*6nhb*” exhibited similar number of sylleptic long shoots to that of “*7nhb*” and differed only in the number of proleptic short shoots. Of all pruning intensities, branching zones for “*3nhb*” and “*4nhb*” were shorter than sylleptic branching zones. “*5nhb*” was characterized by the same length of branching zone and sylleptic branching zone. “*6nhb*” to “*9nhb*” were similar to “*3nhb*” and “*4nhb*”in the length, while “*10nhb*” to “*12nhb*” showed shorter sylleptic branching zone.

DISCUSSIONS

Considering a succession of lateral types along pruned parent shoots as discrete branching states outlined the presence of distinct zones within which the lateral type composition was homogeneous, but changed among zones. This structure was invisible as it could not really be found in qualitative observations. Among three pruning intensities, “4nhb” representing severe heading back had a strong branching potential which appeared in the measured and simulated results, such as the first occurrence of long or sylleptic shoots. It also turned out that the probability of basal budding along pruned parent shoots depends on the number of retained buds close to the actual cutting.

The proportion of branching zones and sylleptic branching zones increased from “3nhb” to “12nhb”. Mean numbers of fruits located in branching zones were twice as many as in sylleptic branching zones (1.7 for “4nhb”, 2.2 for “7nhb”, 1.8 for “12nhb”, respectively). This indicates that the proportion of two types of branching zones provide indication for prediction of fruit production. In comparison with slight heading back (“10nhb” to “12nhb”), moderate heading back (“5nhb” to “9nhb”) had a lower proportion of fruiting zones. As the former pruning intensities is generally regarded as more proper pruning with moderate vegetative and reproductive growth of pruned parent shoots in comparison with the latter, this classification is coherent with the conventional pruning intensities [18].

Three-dimensional structures with detailed leaves and fruits are given in Figure **8** to explore branching and fruiting traits of pruned parent shoot under three pruning intensities.

Simulation results demonstrated that effect of different pruning intensities on branching patterns of parent shoots, it might serve as a flexible platform for fruit tree researches with new point of view. Nonetheless, the shape of fruit trees are also likely to vary with cultivar, rootstocks, and tree age. Therefore, further improvement of models taking into account these conditions remain to be done as a natural continuation of this work.

The stochastic model may easily help to verify more effective pruning techniques to improve pruning efficiency. Moreover, the simulation results provide new insights into biological mechanisms, which can reexamine extra assumptions. For example, the current results could possibly be used to evaluate the outputs of other models, in particular structure-function models [13].

Manipulating the vegetative and reproductive growth relationships might be regarded as the main goal of fruit tree pruning systems. The quantitative analysis on branching and fruiting rules of pruned parent shoots could help to select more effective pruning methods to increase fruit yield and to maintain high quality. It is apparent that the stochastic modeling and simulation of structures and functions of fruit trees will open numerous application areas, including virtual field trials, fruit yield prediction, virtual learning environment, as well as examples of optimization applications, such as planting density, fruit load, and canopy architecture [19].

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