A Stochastic Model to Describe the Fruit Number and Position on Long Peach *(Prunus Persicae)* Shoot

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Abstract: A stochastic model of fruit number and position on a long peach *(Prunus persica cv. yingzhui)* shoot of 10-year-old tree is presented. In model there are generally 3 states in which state 2 represents that a node with two fruits, state 1 represents that a node with one fruit, state 0 represents that a node without fruit. Parameters of model are estimated using the STAT module of Matlab software. The observed data are sampled from mature trees at two harvest seasons during two years in a row (2013-2014) in Lianping, Guangdong, China. Results indicate that upper nodes usually have one fruit, middle nodes have no more than one to two fruits, and most of basal nodes have zero to one fruit. The total number of fruits increases with the number of remaining nodes after pruning. Occupancy distributions of different states in model demonstrate that pruned long shoots had 5 to 7 fruits, whereas unpruned long shoots averaged more than 10 fruits. The fruit distributions on the shoots follow a well-defined pattern: nodes that bear one or two fruits were significantly higher in the median part of the shoot but lower on the basal and distal nodes. In addition, three-dimensional representations of the fruit position were reconstructed using PruningSim software.

Keywords: Prunus persica, Markov chain, Modelling, Stochastic model, Pruning.

INTRODUCTION

In recent decades, more and more mathematical models have made it possible to simulate annual/perennial plant architectures with algorithms, such as rewriting rules in L-system [26] and multiscale tree graph in AMAP mod [4, 6, 14], which provide new insight into the underlying physiological process or control developmental mechanisms [2, 12], and thus, plant modeling, simulation and visualization programs present valuable tools for basic and applied research [37]. This is especially true of fruit trees which will adjust their ongoing growth and development in responding to cultural practices and environmental stresses over the decade- or century-long life span that will also make it very hard to study the influence of these factors in different situations.

Quantitative architectural analysis models focus on branching patterns have been used in some fruit tree species, such as apple [5], peach [7, 34], plum [35] and kiwifruit [27]. However, there is not enough topological information concerning fruiting characteristic of individual tree at shoot level available in the existing scientific literature [13, 15, 17, 22, 28]. Several previous studies have demonstrated the effects of fruit position within the canopy on morphological and physiological quality of fruit [16]. Smith *et al*. (1994) have made spatial analysis of fruit attributes in relation to shoot position in kiwifruit [29, 30]. Hall and Gandar (1996) use a stochastic differential equation to model the fruit size distribution at any time [11]. Lescourret *et al*. (1998) present a simulation model of peach growth that carbon assimilation of fruits is a key consideration [21]. Obvious drawback of some of these models is that they do not take fruit number at each node into account.

Unlike many other tree species, peach has little or no tendency toward alternate bearing [10],and flower buds and leaf buds are borne on one-year shoot produced the previous year, whose number have been demonstrated to be correlated with alternate bearing [19]. Each node along a shoot might possibly have from zero to 3 flower and/or leaf buds. The number and distribution of flower buds on a shoot may vary with scion cultivars, rootstock, shoot vigor, soil, nutrition, and climate [1, 8]. Although some results from field experiments indicate that the number of flower buds per shoot is positively related to shoot length [23, 31], the flower buds borne on short shoot, but more generally, grow into small fruit. Therefore, adequate long shoots, growing out from leaf buds formed during the previous growing season, are necessary to ensure the current season's crop [24, 25]. There is little data available to quantify fruiting characteristic of a pruned shoot.

In this paper, we provide a stochastic approach, Markov chain model, to quantify long shoots in peach. The model focuses on (i) the number of fruits per node, and (ii) the relative position of the fruits along the long shoot. Specifically, we aimed to determine whether fruiting pattern is affected by pruning practices. Furthermore, The realistic three-dimensional visual

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representation for pruning and unpruning shoot are introduced with examples from simulation results using PruningSim software by which the effectiveness of fruit thinning strategies could be evaluated and optimum yield could be achieved.

MATERIALS AND METHODS

2.1. Experimental Site

The study was carried out at two harvest seasons during two years in a row (2013-2014) in at commercial orchard in Lianping, Guangdong Province, China. Topsoil is red loam soil, and average annual rainfall in this area is about 1780 mm. The sampling plots were arrayed in a randomized complete block design with three replications. Each plot composed 25 trees which were 5 rows and 5 trees in each row

2.2. Plant Material

Peach cultivars Yingzui were planted at a density of 1665 trees/ha with a within-row spacing of 2m and between-row spacing of 3m. The open vase tree form was established through the training and pruning of trees along with traditional irrigation and fertilization practices. Yingzui is characterized by self-thinning of short shoots (less than 15cm long), especially on the inside of the tree canopy. Long shoots that grow 20 to 70cm long are very fertile, while some long shoots that have secondary shoots produce fewer fruits. Therefore, the latter should be thinned out during the dormant season. Long shoots without secondary shoots were randomly selected within the tree canopy in the sampling plots.

The pruning treatments consist of light and moderate pruning in which the total 1/5 to 1/3 the length of the shoot from the terminal end is removed, whereas the controls allow the shoots to bear fruits without any pruning. The time for pruning trees was late winter or early spring just before new growing season. Number of fruit at each node along the long shoots was recorded.

2.3. Model Description

Each node along a shoot may have from zero to two fruits in combination with zero or one shoot. Many of the terminal node of a long shoot has a vegetative bud which will develop a shoot. Hence, a simple Markov model with three states is used to model the fruiting habit of a long shoot. The rank of a node along a long shoot consists of an index of a state from which Markov chain can be built. In this context, state 0 represents zero fruit borne on a node, state 1 represents one fruit borne on a node, and state 2 represents two fruits borne on a node.

Examples of Markov chain with different states can graphically illustrate the position and number of fruit (Figure **1A** and **1B**). In these examples, initial probability ($p(S_0=i)$) denotes the probability of the node being a given state at the proximal node of a shoot, with i = 0, 1, 2 where $\sum p(S_0 = i) = 1$. Transition probability (p_{ij}) suggests that the probability of the node being a given state depends only on the probability of the previous state, with i = 0, 1, 2 and j = 0, 1, 2, where $\sum_i p_{ij} = 1$. To compute the total number of fruit on a shoot, occupancy distribution ($o_i(n)$) is used to sum the number of successive nodes being in the same state, when $i = j$, $o_i(n)=(1-p_{ii})^{n-1}p_{ii}$, where n = 1.2, ...∞ and i =0, 1,2.

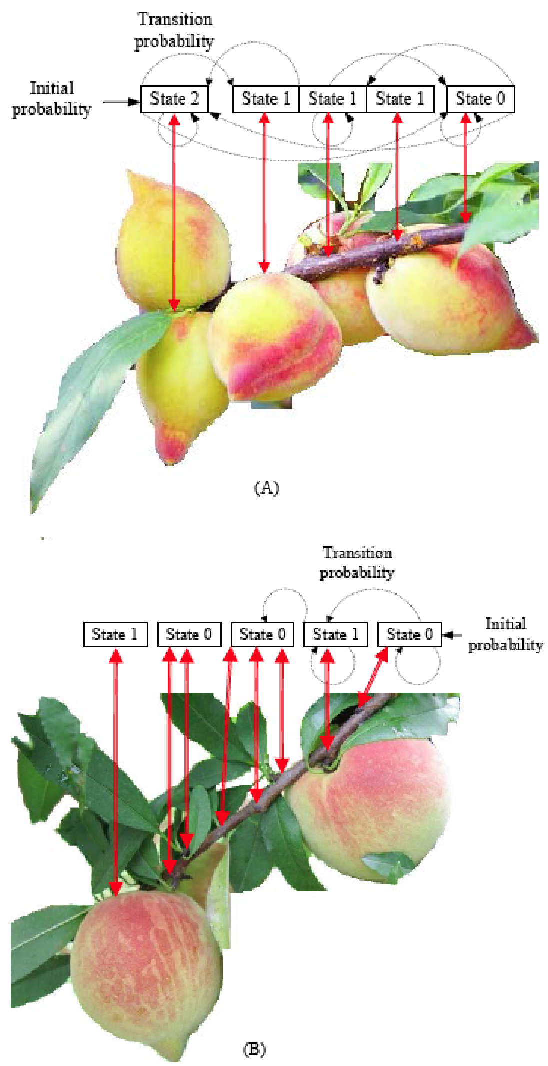


Figure 1: Schematic diagram of three-state (**A**) and two-state (**B**) Markov chain. The transition probability of a state is represented by the broken line and the initial probability of a state by the continuous line.

The observed distribution was estimated by the forward algorithm which will compute the probability of the state for each observation. The Baum–Welch algorithm will be used to estimate the initial probability, the transition probability, and the occupancy distribution of a given state in Markov model from which the theoretical distribution was calculated using the STAT module of Matlab software.

2.4. Simulation and Visualization

The distributions of the fruits along the long shoot can be simulated by the PruningSim software. The basic step for simulation is the output of fruits which depends on the fruiting probabilities in Markov chain, *i.e*. the probabilities of state 0, state 1, and state 2. Some examples of visualization that describe in detail how to run simulations in PruningSim software are available online [36].

RESULTS

1. Position of Fruits on the Long Shoots

Table **1** shows that the initial probabilities of the different states remain constant irrespective of the medium pruning shoots, light pruning shoots or the control shoots. Also, there is no difference in transition probabilities of states between light pruning shoots and medium pruning shoots. These results indicate that bearing probabilities at basal nodes of the long shoots are not easily influenced by pruning practices. Distal nodes at the terminal end of the control shoot do not bear fruits, as indicated by the transition probabilities of state 0. There can be nodes at the median part of the control shoots that do not bear fruits, but many of nodes bear one or two fruits. Light pruning and medium pruning shoots exhibit similar bearing patterns as the control shoots on which a high fruit probability distribution is found at upper and middle nodes.

The characteristic distributions play important roles in the process of model validation. The accuracy of Markov model is evaluated by comparing the theoretical distributions of the state with the observed distributions extracted from the observed data (Figure **1**).

The fruit distribution was examined by the corresponding state occupancy distribution. Observed and theoretical distributions of the state 1, which represent bear one fruit per node, are shown in Figures. **2**, **3** and **4**, respectively. These illustrations highlight the isolation of fruit on the shoots due to the value of 1 is the largest frequency of occurrence of

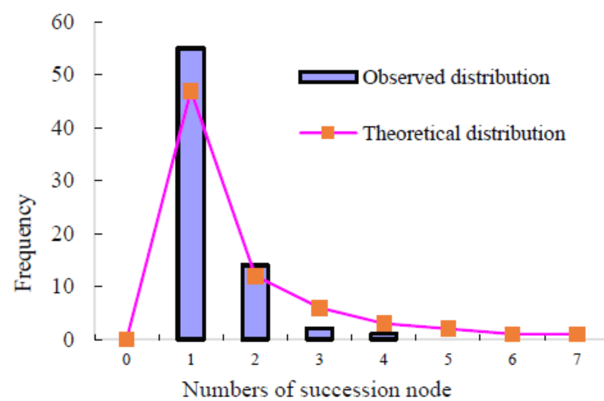


Figure 2: Occupancy distribution of state 1 on the light pruning shoot.

Table 1: Initial and Transition Probabilities of the State in Markov Chain

Pruning Intensities	Initial Probabilities			Transition Probabilities		
	State 0	State 1	State 2	State 0	State 1	State 2
Medium pruning shoots				0.70	0.30	0.00
	1.00	0.00	0.00	0.73	0.27	0.00
				0.75	0.25	0.00
Light pruning shoots				0.70	0.29	0.01
	1.00	0.00	0.00	0.76	0.23	0.01
				0.75	0.25	0.00
CK				0.79	0.20	0.01
	1.00	0.00	0.00	0.81	0.18	0.01
				0.82	0.18	0.00

each state. The larger frequency, the greater the number of occurrence, and vice versa. The frequency of the state 1 is smallest between the values of 2 and 10, indicating the smallest number of successive nodes between those values.

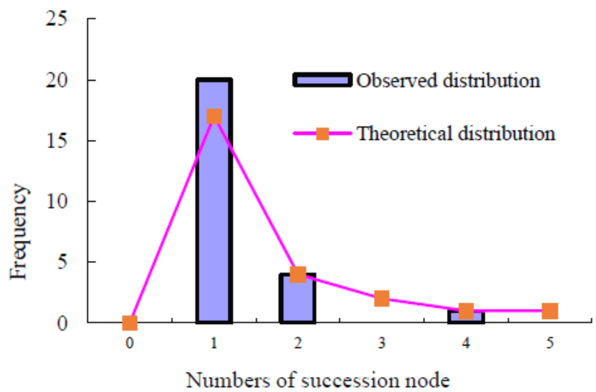


Figure 3: Occupancy distribution of state 1 on the midium pruning shoot.

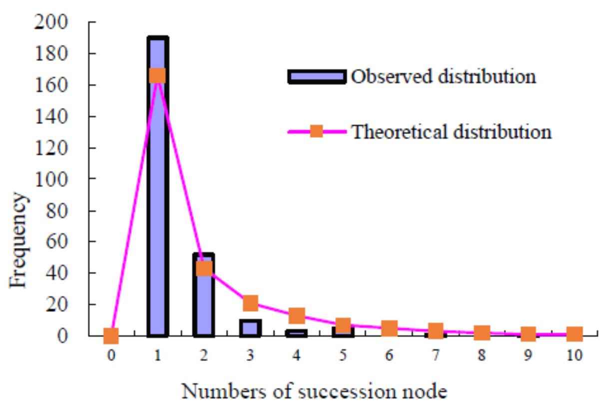


Figure 4: Occupancy distribution of state 1 on the control shoot.

2. Mean Number of Fruit on the Long Shoots

The nodes that do not bear fruit on the pruning shoots is up to 86%, similarly, there are as much as 83% of the nodes on the control shoots do not bear fruit (Table **2**.). The total node number of the state 1 on medium and light pruning shoots rises from 4.45 to 6.46, whereas the total node number of state 2 does not increase remarkably, range from 0.52 for light pruning shoots to 0.53 for medium pruning shoots. As a consequence, 14% of the nodes bear at least one fruit on the medium pruning shoots vs. 15% on the light pruning shoots which indicates there are 5.51 fruits per the medium pruning shoots, while the light pruning shoots can bear 7.50 fruits. By contrast, the nodes on the control shoots can bear 10.57 fruits.

3. Simulation and Visualization

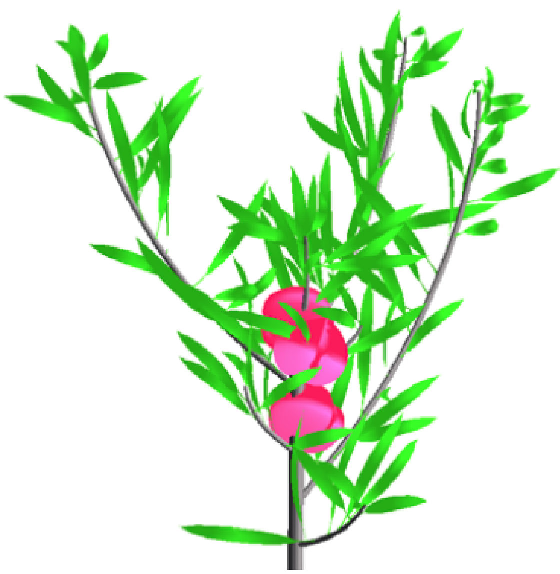
The purpose of simulation and visualization was to test the consistency of model and observed data. A simulation tool, called PruningSim, will create a virtual environment in which a virtual shoot can be pruned numerous times according to one's own knowledge of pruning or desired outcomes (Figure **5**.).

(A)

Table 2: Total Node Number of the State Occupancy Distributions and Mean Number of Fruits on the Long Shoots

Pruning Intensities	Total node Number of Occupancy Distribution			Mean Number of Fruits Per Shoot	Proportion of Fruiting Node
	State 0	State 1	State 2		
Medium pruning shoots	35.02	4.45	0.53	5.51	0.14
Light pruning shoots	41.02	6.46	0.52	7.50	0.15
CK	50.01	9.41	0.58	10.57	0.17

(B)



(C)

Figure 5: Simulation results of fruit distribution on the control shoot (**A**), light pruning shoot (**B**), and medium pruning shoot (**C**).

The results of these numerous simulations can give a user a most likely case, along with a probability for each state to understand the stochastic characteristics of fruit distribution on different shoots.

DISCUSSIONS AND CONCLUSIONS

Pruning is an effective way of regulating the vegetative and reproductive growth interaction. Shoot pruning combined with fruit thinning are, in fact, the key for ensuring sustainable fruit production of high quality [9]. However, some field observations showed that heavy pruning might lead to increase in the proportion of long shoot [18], which cause excessive vegetative growth with fewer flower buds. By contrast, light and medium pruning favors reproductive growth [33]. Some results from field experiments indicate that fruit size increases as shoot length increases, and declines as crop load per shoot increases [20]. Our results also suggest that there is relationship between fruit number and shoot length. But nodes on the control shoots tend to produce small fruit because there is not adequate assimilate available for fruit growth. Therefore, light and medium pruning must be practices to maintain leaf-fruit ratio each year. Both light pruning and medium pruning shoots show higher percentage of large fruits in comparison with control shoots. The ideal pruning long shoot has 5-7 fruits at its median and distal nodes.

The nodes that bear one fruit are located primarily at middle parts of the shoots. Medium pruning shoots have higher proportion of nodes with 2 fruits in comparison with light pruning shoots. The occupancy distributions of the states 0, 1 and 2 characterize a rather scattered bearing pattern on pruning shoots. This pattern is more pronounced on control shoots.

The leaf buds at most nodes of pruning shoots develop into the proleptic shoots that can bear fruit in subsequent growing season. Many of buds on unpruned shoots produce the sylleptic shoots in which fewer flower buds are formed [34].

Numerous studies have emphasized the importance on fruit-thinning for fruit quality [3, 32]. A fruit distribution model can help to optimize thinning strategy, and predict fruit yield in response to horticultural practices. The simulation results (presented above) demonstrate that Markov models represent the stochastic growth much more realistically than those models based on deterministic functions. The model can now be applied to peach trees but there is no restriction its application to other fruit trees.

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