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African Journal of Agricultural Research Vol. 6(13), pp. 3071-3077, 4 July, 2011
Available online at http://www.academicjournals.org/AJAR
ISSN 1991-637X ©2011 Academic Journals

*Full Length Research Paper*

# Growth and development simulation based on functional-structural model GreenLab for poplar (Salicaceae)

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Accepted 15 June, 2011

**Poplar (salicaceae) is one of the widest planted fast-growing trees in the world. It is not only used for timber, but also used as windbreak and ecological protection of forest widely. The architecture of poplar has direct impact on poplar's growth and applications, but poplar's architecture still has not been discussed deeply in previous poplar models because of the difficulties raised by measurement, data processing and parameterization. This paper aimed to collect the biomass and architecture data of poplars of different ages, and construct the functional-structural model of poplar based on GreenLab. The selected poplar variety was poplar 107 (Populus × euramericana cv. Neva). The biomass and architecture data were collected from four trees with 3, 4, 5 and 6 years old, respectively. The architecture was simplified by classifying the branches into several types (physiological age) according to the length and size. Based on GreenLab model, some parameters were obtained and some strong correlation coefficients were got. The comparison between the measured and simulated results was given for the trunk data of all trees. The topological structures of poplar at different tree ages were reconstructed. This paper was a exploration of poplar growth simulation based on GreenLab model, and was a good reference in the Functional-Structural model construction of complex trees.**

**Key words:** Poplar, Populus × euramericana cv. Neva, GreenLab, growth and development, parametric identification.

## INTRODUCTION

Poplar is a member of salicaceae, which is the main species for windbreaks and timber in plain and sand (Bradshaw et al., 2007). It has a wide variety and is extensively distributed throughout the world. At present, poplar has been cultivated worldwide for paper, wood products and energy. Moreover, it has been widely used in windbreak and for soil erosion control, and has proven to be capable of remedying environmental toxins (Flathman et al., 1998) and indicating the ozone pollution in the environment (Jepsen et al., 1994). The external architectures of poplar, such as trunk straightness and the crown shape, have a direct impact on the quality of its stock volume. So the researches on how to enhance the production of timber by optimizing the external environment conditions are important for the forestry industry.

Since the 70's, in order to meet the increasing demand of wood in energy consumption and timber industry, scientists in North America, Europe and other regions have carried out several studies on the management of perennial woody plants. As the poplar is one of the best fast-growing trees, the research on poplar has always been taken seriously. The focus of poplar

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**Abbreviations: GU,** Growth unit; **PA,** physiological age**; CA,** chronological age; **SLW,** specific leaf weight.

researches is on combining physiology with morphology to understand the growth and the development of poplar. In some studies, the mechanism and morphology was considered on the basis of measurement data (Liu et al., 1993; Rauscher et al., 1990; Li et al., 1994; Zhou et al., 2007). Some studies focus on how to improve the yield of poplar (Chen et al., 1998; Hao et al., 1989; Wang et al., 2004). There are also some studies that concentrate on poplar physiology, such as the effects of light intensity (Wang et al., 1993), carbon dioxide (Wang et al., 1993), soil moisture (Jia et al., 1997), leaf area and meteorological data (Zhang et al., 2006) on the photosynthetic rate and transpiration rate of poplar. These models generally lack information on the interaction between plant morphology and environment, but the architecture has an important effect on production, so these models cannot effectively control the production and cultivation.

The plant architecture is increasingly recognized to be important in plant performance, and should be taken into account in modeling (Birch et al., 2003). The study of plant architecture emerged as a new scientific discipline since 30 years ago, and developed rapidly from then on (Smith et al., 1992; Evers et al., 2007). On the other hand, for applications in agronomy and forestry, the biomass production and distribution must be taken into account in the plant growth modeling, which leads to the research of functional-structural model (Sievanen et al., 2000; Prusinkiewicz et al., 2004). They are potentially possible to simulate the interaction between the architectural development of plants and their physiological function. At present, there have been many existing functional-structural models, such as ECOPHYS (Rauscher et al., 1990), LIGNUM (Perttunen et al., 1996), GreenLab (Zhan et al., 2003), L-Peach (Allen et al., 2005). Although these models have been used to simulate the growth of some trees very well, the accuracy and computing complex in parameter estimation still becomes a huge obstacle when simulating trees with a large number of organs (Letort et al., 2008). GreenLab is a functional-structural plant model that has been developed for 10 years. In GreenLab model, the parameters were estimated through the generalized least squares method (Zhan et al., 2003) and a multi-fitting technique is used to estimate parameters which simultaneously minimizes the error between model output and the target file data defined from measurement data, therefore greatly enhancing the accuracy of parameter estimation (Guo et al., 2006). Furthermore, in GreenLab model, the growth simulation of tree and the calibration of data can be simplified, making it easy to deal with trees with complex architecture. GreenLab has been applied to many plants such as corn (Guo et al., 2006), sunflower (Guo et al., 2003), potatoes (Dong et al., 2003), Chinese pine sapling (Guo H et al., 2006), and beech tree (Letort et al., 2008).

A grown poplar has complex architecture and large number of organs. It is a challenging task to simulate the poplar's growth process, especially to simulate the interaction between its architectural development and physiological function. In this paper, we study the growth of poplar based on GreenLab. We first briefly introduce the principle of the GreenLab, thereafter demonstrate some direct results obtained from measurement data, and finally we present some fitting process and simulation results of poplar.

## MATERIALS AND METHODS

### Plant materials and sampling

The Poplar variety studied is poplar 107 (Populus×euramericana cv. Neva) that has short growth period, quick growth speed, good material quality, strong resistance, easy vegetative propagation, and broad accommodation range. Poplar 107 has already passed a national certification, and won a third prize of the National Prize for process in Science and Technology. Now it has been widely used for afforestation of trees and for high grade paper pulp raw materials. Moreover, it plays an important role as raw material in industrial and is one of the main strains that have been extended broadly.

Samplings and measuring were implemented in June, 2008 at the forestry center of Fugou county, Henan province(34°3′N, 114°23′E). In the forestry center, poplars were spaced in field three meters in width and four meters in length. Four trees that had been growing 1, 2, 3, 4 years were selected and destructively measured respectively. The four trees are denoted tree 1, tree 2, tree 3 and tree 4. In the beginning, these trees were plugged in the spring and implanted to the nursery garden in fall. In the next March, they were replanted to the field where the sampling was made, so the real age of these trees are actually 3, 4, 5, 6 years, respectively.

We implemented destructive measurement on each sampling tree. For each tree, we cut and measured its branches. There are a lot of branches in each tree and measuring all the branches in details would be a very tedious work. Considering the branches growing on the same growth unit (GU) of one axis have the similar structure, we simplified the measurement by just sampling one or several representative branches to measure according to their length and morphological characteristics. For each sample branch, the fresh weight, length, diameter and the number of leaf scars of each GU were measured. In addition, leaves of every tree were divided into three types by size, as big, small and medium. We picked three sample leaves of each size, and the fresh weight and surface of each sample leaf were recorded. The leaf surface area was obtained by taking a photo of each leaf, and computing the surface area with image processing method.

The values of internode allometric parameters, leaf thickness, internode sink strength and leaf sink strength used in GreenLab can not get good results, because of the deficiency of data. In September, 2009 we went to the forestry center and make further measures to supplement some data to get better results. We mainly supplemented the data of newborn internodes and blade, including internode fresh weight, internode diameter, internode length, blade fresh weight and blade surface. We used electronic balance, which has higher measuring accuracy, to weigh the leaf fresh weight and internode fresh weight this time (the accuracy is 0.01 g).

### GreenLab model

GreenLab is a functional-structural model for agronomy and forestry applications. It simulates biomass production and allocation with a source-sink model. Detailed information on Greenlab can be

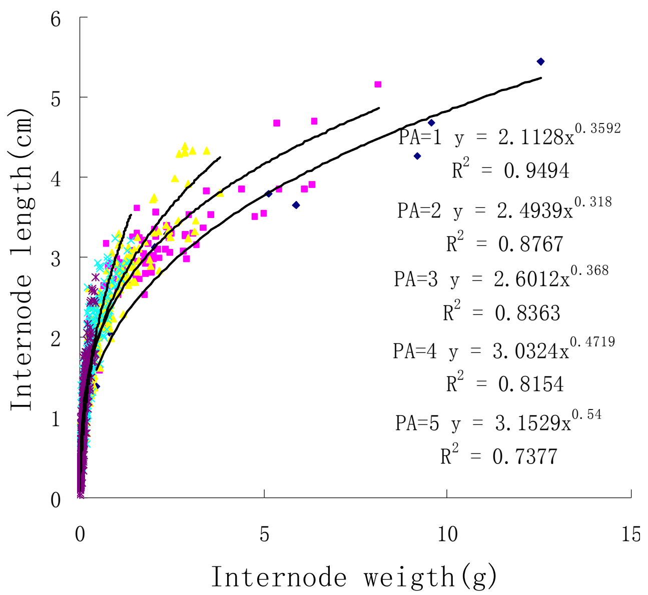


**Figure 1.** Internode allometry parameter.

referred to in previous papers (Sievanen et al., 2000; Yan et al., 2004) and a tutorial is available on website (www.greenscilab.org).

GreenLab has three versions (GL1, GL2 and GL3).GL1 is the simplest feature of GreenLab. The virtual plant is deterministic, and there is no interaction between plant growth and plant development. GL2 is stochastic and GL3 is deterministic with retroaction between plant growth and plant development. This paper is of the primary result, and only the deterministic version is used to fit the model. I.e. we don't take the stochastic and environment variations into account. The multi-fitting method (Guo Y et al., 2006) was used to optimize parameters in our study. This method permits simultaneous optimization of all relevant parameters with several independent target file (a description of plant topological structure) and can construct identical phenotypes through implementing the same rules and parameters.

## RESULTS

### Classification of branch physiological age

In the target file, we define each axis in accordance with the physiological age (PA) and chronological age (CA), and describe it by GU with average weight, length and diameter of internodes and with average weight and area of blade. CA is the plant age. PA is the number of states for axis differentiations in a plant, which characterizes the potential evolution strength (Letort et al., 2008). In this paper, the PA of an axis was determined with its length and characteristics of the branch and under the following constraints: The PA of the main axis is 1. The PA can't be greater than 5. The PA of the axis must be bigger than the PA of its bearing axis. As in Figure 5, different color is of different PA. We can see that the branch with smaller PA has more complex structure and bigger size.

### Internode allometric parameters and specific leaf weight

In GreenLab model, the organ shape is derived from its current mass using simple allometric rules (Guo et al., 2006). For the internode, we assume its shape as a cylinder, defined by 2 parameters $b$ , $\beta$ :

Length: $$L = \sqrt{b} \cdot q^{\frac{1+\beta}{2}} \tag{1}$$

Where $L$ is the length of internode, $q$ is the fresh weight of internode. So $b$ and $\beta$ can be estimated by analyzing the experimental data of weight and length of internode. We can see from Figure 1 that the internode length and internode weight have a strong index relationship. The estimated results of internode allometric parameters are listed in Table1.

As shown in Figure 2, the ratio between the leaf weight and the leaf surface is typically constant, which means the specific leaf weight (SLW) is basically constant. So in the simulation the SLW of leaves was set to be a constant whatever its contour.

### The sink strength of the internode

We assume that the newborn leaves and internodes are generated immediately because their growth period is much shorter than one growth circle (one year). It means that there is a simple proportional relationship between the newborn internode weight and the newborn leaf weight. Thus the sink of an organ "o" is estimated as:

$$P_o(k) = \frac{q_o(k)}{q_a(1)} \tag{2}$$

Where $q_o(k)$ is the average mass of the organ "o" whose PA is k. $q_a(1)$ is the average leaf fresh weight on the tip of the main stem (PA is 1). We consider the sink strength of the leaf in the main stem as a reference value, which was set to 1. So the sink strength of each organ of different physiological age is a relative value, and we can get the internode sink strength and leaf sink strength from the ratio between internode weight and leaf weight of the new growth unit. Figure 3 shows the ratio in each PA. The result indicates that there is a strong linear relationship between leaf mass and internode mass in each PA. The internode sink strength and the blade sink strength of each PA are listed in Table1.

**Table 1.** Values of sink, allometric parameters and hidden parameters.

| Parameter | | Value | | | | |
|---|---|---|---|---|---|---|
| | | PA1 | PA2 | PA3 | PA4 | PA5 |
| $p_e$ | Internode sink | 0.875 | 0.5437 | 0.1671 | 0.0559 | 0.01478 |
| $p_a$ | Blade sink | 1.00 | 0.6594 | 0.3188 | 0.1596 | 0.07323 |
| b | Internode allometry | 4.4639 | 6.2195 | 6.7662 | 9.1955 | 9.9408 |
| β | Internode allometry | -0.2816 | -0.364 | -0.264 | -0.0562 | 0.08 |
| ε | SLW ($g.cm^{-2}$) | 0.023 | | | | |
| $Q_0$ | Initial seed biomass (g) | Tree1, 52.97; Tree2,128; Tree3,80.56; Tree4,185 | | | | |
| R | Blade resistance | 1.87185 | | | | |
| $p_c$ | Relative sink strength of ring | 0.0083 | | | | |

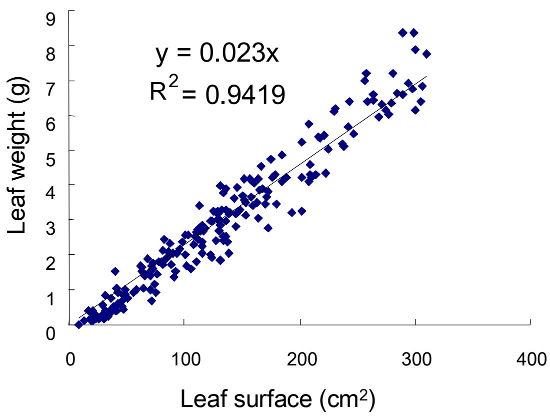


**Figure 2.** Specific leaf weight.

## Fitting the target data

The hidden parameters of GreenLab are inversed by the model through target file. In this paper, the data of four trees were multi-fitted that greatly enhanced the accuracy of parameter estimation.

Based on the measured data of poplar, most parameters can be obtained directly, only a few parameters need to be fitted: the initial seed biomass $Q_0$, the coefficient for leaf resistance R and the relative sink strength of ring demand pc. Calibration results are illustrated in Table1. Figure 4 illustrates the comparison between simulated results and measured data. The fitting graphs represent internode mass (Figure 4a) and internode diameter (Figure 4b) GU by GU on the main stem. Although the fitting is imperfect, the global trend is correct.

## Simulation of plants

The structures of the four trees are reconstructed in Figure 5. The visualization effects of these trees are still not very realistic, as some geometrical parameters, such as the positions of each branch, the curve shape of each axis, are not measured but given artificially, while the topological structures are authentic.

## DISCUSSION

As a functional-structural model, GreenLab has been widely used in crops, and some preliminary work has also been done on trees, such as pine and beech tree. This paper studies the poplar growth based on GreenLab. It explores the ratio of the fresh weight of leaf and internode with experimental data, estimates the model parameters by model inversion, constructs the simplified topology, and completes the simulation of poplar growth.

Our work is a preliminary study. Although the identified model parameters approximate the results, much more research is still needed. First, the secondary growth is not considered in this paper. The root biomass is set to be a constant currently. We can further collect corresponding data and defining the sink-source model of root system to improve the simulation result. Second, the environment variable is considered to be a constant in this paper. In our later work the environmental factors will be integrated in the growth of poplar. Third, in the simulated tree structure of Figure 5, the distribution of branches is set automatically by the model. These branches are set too concentrated to be adequately realistic in visual effects. Further work can be done to collect distribution information of branches to improve the visual effects of simulation results.

## ACKNOWLEDGEMENTS

We thank the students and Henan Bureau of Forestry involved in collecting the experimental data. In the work, the study of plant growth simulation was supported by National Higher-education Institution General Research and Development Foundation in Beijing Forestry

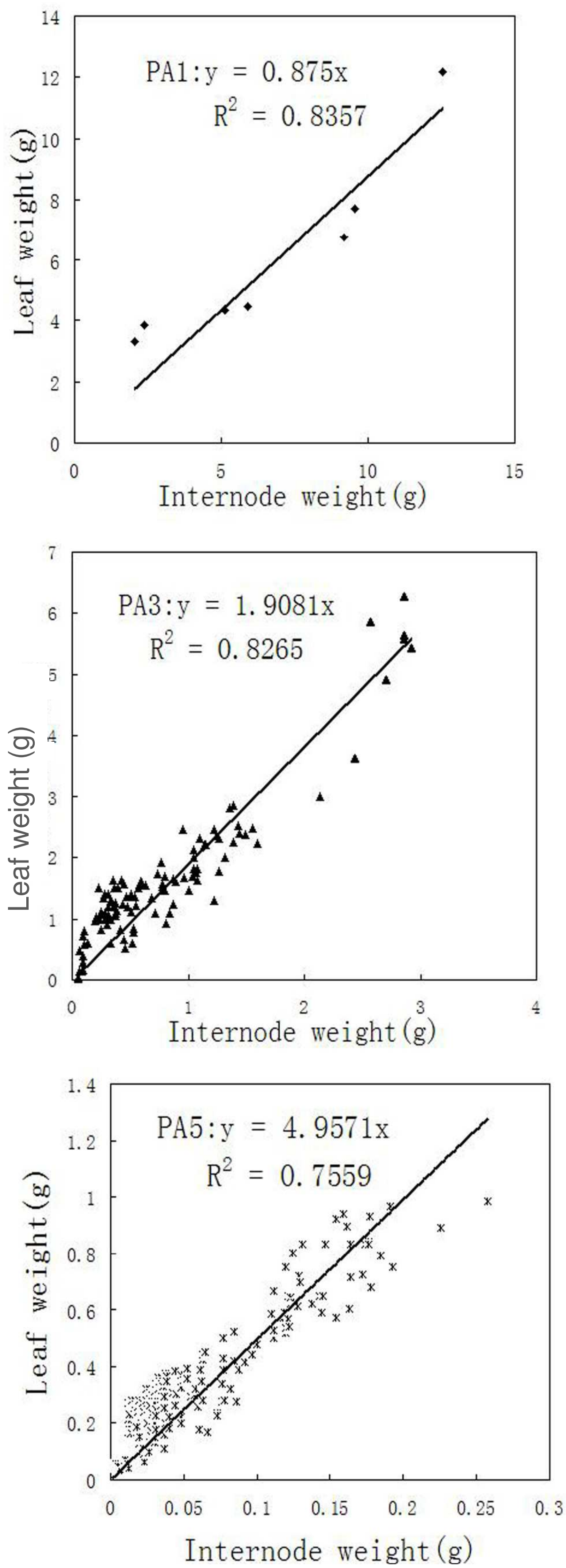


**Figure 3.** The fresh weight ratio between the leaf and the internode at the same GU in each PA.

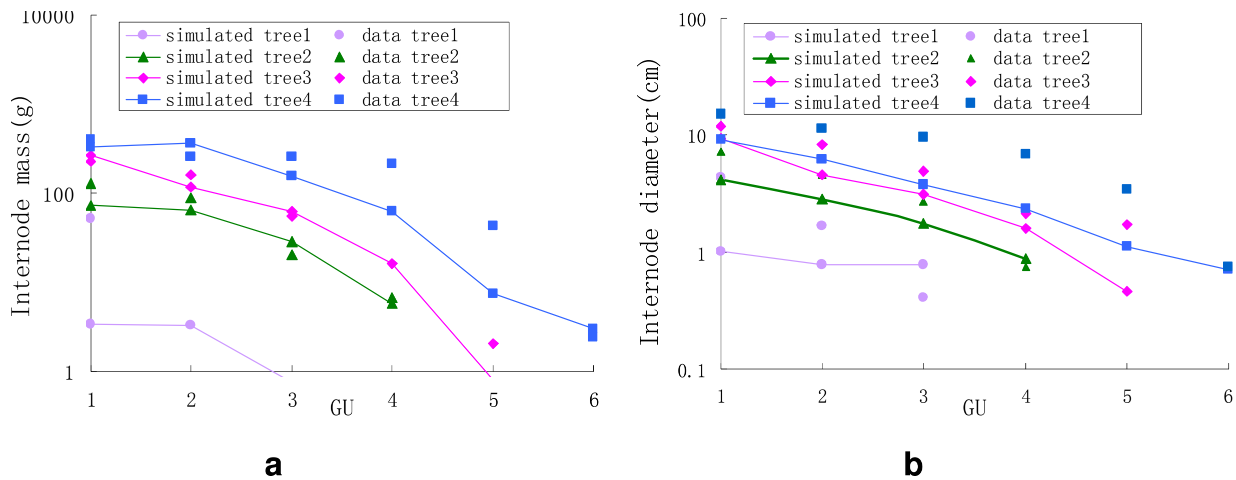


**Figure 4.** Multi-fitting results.


**Figure 5.** Structures of tree1, tree 2, tree 3 and tree 4 based on the fitted parameters (without leaf).

University (No. YX2011-38); the study of plant visual simulation is supported by National "948" Program of China (No. 2009-4-41); the data measurement and data fitting are supported by National Natural Science Foundation of China (No.60703006) and the National Basic Research Program of China (973 Program, No.2009CB119107).

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