A Nonlinear-matrix Model for the Prediction of Mixed Uneven-aged Forests
Growth with FORTRAN Program in Changbai Mountain, China

Yang Liu, Xingang Kang, Yanrong Guo, Jinghui Meng

Abstract

To compare the growth dynamic of the natural forest without any management practices with the forest under selection cutting regime in the Changbai Mountain, based on FORTRAN program we developed a simulator which inherently imbedded nonlinear growth model combined with matrix model. The nonlinear ingrowth and upgrowth models were established by the stepwise regression and mortality models were built for the small, medium and large diameter class by the empirical equation, all of which were combined with the matrix model to predict the growth dynamic of mixed uneven-aged forests. Chi-square test was used to test these models and no significant difference was observed between the actual and theoretical number of trees, which indicated the efficiency of the simulator developed. We applied the simulator and the result showed that basal area and volume of stands for the forest under selection cutting regime was significantly higher than the natural forest without any management practice (basal area: 35.6:18.4; volume 284.5:147.5). We concluded that the selection cutting could promote growth and yield of forest stands i.e. the forest could produce more volume if we conducted selection cutting than the forest with no management practice. The simulator developed in this study could be a useful tool for projection of current stand and therefore contribute to forest management planning.

Keywords: Nonlinear Growth Model, Matrix Model, Growth Prediction, Simulator, Spruce-fir Mixed Forests

1. Introduction

Uneven-aged forest stands are characterized by a nonuniform spatial arrangement of trees with age, size and even species varying over the area [1]. In the Changbai Mountain, uneven-aged mixed-species forests constitute 59% of the total forest area and play a significant role both to the regional ecological and economical aspects [2][3]. Due to the importance of this kind of forest, a large number of studies have been conducted. Tan et al. use forest inventory datasets and NOAA/AVHRR normalized difference vegetation index data to estimate forest biomass C stock and its changes in this region [4]. The other research has been previously carried out on forest community classification [5], forest structure and tree species composition [6], tree-ring analysis [7] and old-growth studies [8]. For previously these valuable researches, fewer have concern with forest dynamics which is also of great significance to forest management planning.

Growth and yield models are important tools for projecting forest dynamics and furthermore it allows us to predict the stand development and yield under various management scenarios [9][10]. Three types of growth and yield models are normally used: tree-level models, size-class models and whole-stand models.

In this study, we used matrix models which are one type of size-class models to simulate the forest growth dynamics. Matrix models, also known as transition matrix models or matrix growth models which were initially used to describe animal population dynamics are widely employed in forestry research [11][12]. It was Usher who firstly introduced Leslie matrix model to simulate uneven-aged forest dynamics. Since then, more and more attentions have been ever paid by many foresters. Liang et al. use matrix transition models to explain climate impact on forest population dynamics, both at the landscape and regional level. The model predicted that the basal area increment in the region under natural succession would be hindered by global...
warming, more so for dry upland areas than for moist wetlands [13]. To determine the optimal harvesting strategy for uneven-aged mixed-species stands, Hao et al. built a matrix model which involved residual basal area, diameter of the largest tree, harvest cycle and a constant $q$ which represented the ratio of the number of trees in a given diameter class to those in the next larger diameter class as dependent variables. According to model simulations, the respective harvesting strategies are both defined for the objectives of maximizing net revenue and total volume yield [14].

Buongiorno et al. used a matrix model to forecast long-term growth of undisturbed and managed stands. The parameters in this model included upgrowth (stochastic transition of trees between diameter classes) and ingrowth (new recruitment in forest stand), both of which were estimated as constant values for the simulation. In reality the parameters (ingrowth and upgrowth), however, are not constant and might be variant in different size classes. As a result, the prediction might induce a biased estimation [15]. Zeng et al. used a linear model to predict the growth dynamic of uneven-aged forests under nature and selection cutting condition [16]. A generalized linear mixed model and logistic regression model were built and independently used to predict the probability of individual tree mortality over discrete time periods in uneven-aged stands management under a selection system [17][18]. However, very few studies were carried out using nonlinear system growth model in conjunction with matrix model to simulate and predict the growth dynamic of mixed uneven-aged forests.

In this study, we estimate the parameters (ingrowth and upgrowth) as variant rather than constant in the former studies and combine nonlinear system growth model with matrix model together to simulate the forest dynamics. The main objectives are to (1) build a nonlinear ingrowth model; (2) develop a nonlinear upgrowth model; (3) establish a nonlinear mortality model; (4) construct a transition probability matrix model and conduct simulation and prediction for natural mixed uneven-aged stands using FORTRAN program.

2. Methods and data analysis

2.1. Study area and plot measurement

The study area is located at the Jingouling Experimental Forest Farm (43°22'N, 130°10'E), Jilin Province, in Changbai Mountain, Northeastern China. The average annual temperature is about 3.9 °C and the annual precipitation is 600-700 mm, mostly in July [19]. Early frost started from mid-September and late frost end at the end of May, with an average growth period of about 120 days. The altitude of the area ranges is 300-1200 m and the slopes of mostly vary between 5° to 25°. Soil type belongs to dark brown forest soil and the average thickness is about 40 cm. The main species in this area are spruce (Picea asperata), fir (Abies fabric), Korean pine (Pinus koraiensis), birch (Betula costata) and linden (Tilia amurensis) [20]. The original vegetation type is mixed broad-leaved Korean pine (Pinus koraiensis) forest. After long term anthropogenic disturbances, the forests have been converted to spruce-fir dominated mixed coniferous forests and birch-aspen mixed broad-leaved forests.

In this study, we used 96 permanent sample plots which were established in 1986 in dominate forest type i.e. spruce-fir forest for model construction and forest dynamic simulation. The plot size ranged from 0.12 ha to 0.21 ha. These plots were continuously surveyed for the 24 years from 1986 to 2009. Each five years was regarded to be a growth period. Till now, there were four growth periods from the initial plot establishment to final investigation. All trees in the plots ($d_{1.3} \geq 6$ cm) were numbered and tagged at 1.3 m above the ground for repeated diameter measurement. Besides, mortality for trees ($d_{1.3} \geq 6$ cm), ground diameter and number of seedlings and saplings for the main tree species were recorded.

2.2. Data analysis

We grouped each tree into different diameter classes with 4 cm width and use 5 years as time interval for model construction. The stepwise regression method was employed for building ingrowth and upgrowth models and mortality model was built with empirical equation. The
fitting models were tested by chi-square test. The R software was involved for the statistical analysis. The Fortran PowerStation 4.0 was applied for producing the simulator to projection purpose of the growth dynamic for stands based on the natural growth and selection cutting condition.

2.3. A growth model of the uneven-aged stand

This study applies structured transition matrix model for predicting the uneven-aged stand growth [21][22]. After a specified growth cycle \( \theta \), the number of living trees in each diameter class of the uneven-aged stand will change. This change could be represented by the following equations:

\[
X_{i+\theta} = a_i (x_i - h_i) + I_i \\
\vdots \\
X_{I+\theta} = a_I (x_I - h_I) + b_{I-1} (x_{I-1} - h_{I-1})
\]  

(1)

Where \( a_i \) represents the probability that a tree stays alive in the same diameter class \( i \) between the time \( t \) and \( t+\theta \), \( b_{i-1} \) is the probability of upgrowth from diameter class \( i \) to the next diameter class \( i+1 \) between \( t \) and \( t+\theta \), \( I_i \) is the number of ingrowth trees per hectare from time \( t \) to \( t+\theta \), \( x_{it} \) is the number of living trees per hectare in diameter class \( i \) at time \( t \), \( h_{it} \) is the number of trees harvested per hectare in diameter class \( i \) to the time \( t+\theta \) from time \( t \), \( i \) is the diameter class (\( i=1, 2, 3, ..., n \)), and \( \theta \) is period interval between inventories.

The equation (1) could be expressed by transition matrix form:

\[
X_{i+\theta} = G (X_i - H_i) + C
\]

(2)

Where \( X_i \) is a column vector representing the number of live trees per hectare in each diameter class at time \( t \), \( H_i \) is a column vector representing the number of trees harvested per hectare in each diameter class at time \( t \), \( G \) is a state-dependent matrix describing transition and staying probabilities of the trees between \( t \) and \( t+\theta \), \( I_i \) is the number of ingrowth per hectare from time \( t \) to \( t+\theta \), \( C \) is a vector of constant.

2.3.1. Ingrowth growth model

According to Ek (1974), the ingrowth is positively correlated with the number of trees and negatively correlated with the residual basal area in the same site quality [23]. The ingrowth model can be expressed as:

\[
I_i = \beta_0 + \beta_1 \times f_1(N) + \beta_2 f_2(B) \quad \beta_0 \geq 0 \quad \beta_1, \beta_2 < 0
\]

(3)

Where \( I_i \) is the number of ingrowth from time \( t \) to \( t+\theta \), \( f_1(N) \) and \( f_2(B) \) are the functions whose independent variables are the number of trees (\( N \)) and residual basal area (\( B \)), respectively, and \( \beta_0, \beta_1 \) and \( \beta_2 \) are the regression coefficients to be estimated.
2.3.2. Upgrowth model

The probability of upgrowth in each diameter class of stands were calculated with formula (4) [16][24] by taking into consideration the diameter increment (cm) of each live tree that was tagged at the time of the study’s establishment during a 5-year interval.

\[ P_{i+k,i} = 1/n \sum_{j=1}^{n} \Delta d_{ij}/w \]  

Where \( w \) is the width of the diameter class, \( n \) is the number of live trees in diameter class \( i \) at time \( t \), \( z_{ij} \) (\( z_{ij} \geq 0 \)) is the diameter increment (cm) of the \( j_{th} \) live tree in diameter class \( i \) between \( t \) and \( t+\theta \), and \( P_{i+k,i} \) is the transition probability of trees in diameter class \( i \) between \( t \) and \( t+\theta \), \( k \) is the number of rising diameter class, when \( k=0 \), \( P_{i+0,i} \) represented the probability with which the trees remained in the original diameter class \( (a_{i}) \), when \( k \neq 0 \), \( P_{i+k,i} \) represented the probability with which the trees jumped to the \((i+k)_{th}\) diameter class \( (b_{i}) \).

Obviously, there is relationship amongst probabilities of upgrowth, retention and mortality in diameter class, which could be represented by the following formula:

\[ \sum_{i=1}^{m} P_{i+1,i} = 1 - m_{i} \]  

For the above equation (6), if \( k=1 \) (the most normal case), the equation (6) could be simplified into the equation (7) with which growth matrix \( G \) could be calculated (In this study, nine trees which came from one of the four sample plots in all sample plots rose two diameter classes during the five-year growth period. At the same time, the diameter at breast height measurement itself had the measurement error. Therefore, the probability of rising two diameter classes can be neglected).

\[ m_{i} = 1 - a_{i} b_{i} \]  

Where \( m_{i} \) is the probability of trees mortality in diameter class \( i \) between \( t \) and \( t+\theta \), \( a_{i} \) represents the probability that a tree stays alive in the same diameter class \( i \) between \( t \) and \( t+\theta \) (when \( k=0 \)), and \( b_{i} \) is the probability of upgrowth from diameter class \( i \) to the diameter class \( i+1 \) between \( t \) and \( t+\theta \) (when \( k=1 \)). We employed the model suggested by Zeng et al. to predict transition probability of upgrowth \( (P_{i+1,i}) \) [24]:

\[ P_{i+1,i} = \beta_{0} + \beta_{1} D_{i}^{2} + \beta_{2} D_{i} + \beta_{3} 1/[g_{1}(N)] + \beta_{4} g_{2}(B) \]  

Where \( P_{i+1,i} \) is the transition probability of rising one diameter class in diameter class \( i \) between \( t \) and \( t+\theta \), \( g_{1}(N) \) and \( g_{2}(B) \) are the functions whose independent variables are the number of trees \( (N) \) and residual basal area \( (B) \), respectively, and \( \beta_{0}, \beta_{1}, \beta_{2} \) and \( \beta_{3} \) are the regression coefficients to be estimated.

2.3.3. Trees mortality model

Instead of building a mortality model for the whole forest stand, we grouped trees into three diameter classes (6 to 12 cm as small diameter class, 14 to 24 cm as medium diameter class, more than 26 cm as large diameter class) [25] for which tree mortality models were respectively made since the mortality varies in different diameter classes. We used the empirical equation developed by Xu to construct the tree mortality probability model \( (m_{i}) \) [26]:

\[ m_{i} = \beta_{0} B^{0.5} + \beta_{1} B + \beta_{2} B^{2} + \beta_{3} x_{i}^{0.5} - \beta_{4} D_{i} + \beta_{5} D_{i}^{2} + \beta_{6} \]  

Where \( m_{i} \) is the probability of tree mortality in diameter class \( i \) between \( t \) and \( t+\theta \), \( B \) is the stand basal area per hectare at time \( t \), \( x_{i} \) is the number of live trees per hectare in diameter class \( i \).
at time $t$, $D_i$ is the average DBH of live trees in diameter class $i$ at time $t$, and $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ and $\beta_6$ are the regression coefficients to be estimated.

### 2.4. Framework of developing prediction systems (simulator) and its application

**Figure 1.** Flow chart of the growth dynamic prediction model for uneven-aged forests

FORTRAN is the most preferred language among the high performance computing community [27]. The design of the prediction systems includes the process of model establishment and stand projection, which is shown in Figure 1. The model establishment can be divided into the following steps: (i) count number of trees for the ingrowth, upgrowth and mortality and calculate the upgrowth and mortality probability in each diameter class; (ii) estimate model parameters and build the ingrowth, upgrowth and mortality models, respectively; (iii) test models using Chi-square test. For stand projection, including the following steps: (i) input the average basal area and density of number of trees for stands, the midpoints of diameter classes and number of trees in each diameter class into the established models to calculate the growth matrix $G$; (ii) calculate the number of trees to be harvested by the selection cutting intensity with an one-parameter (DBH) volume table; (iii) input number of trees in each diameter class and width of the diameter class, and then use the code of Fortran program to predict the number of trees for each diameter at the final interval stage.

### 3. Results and analysis

#### 3.1. Ingrowth model

On the basis of the Equation (3), the ingrowth model was developed by stepwise regression as follows:

$$I_t = 531.912 - 3356.697 \ln N - 1 - 5.17 \ln B_i$$

$$R^2 = 0.62 \quad (10)$$

As equation 10, the ingrowth is positively correlated with the number of trees and negatively correlated with the residual basal area. The same result was reported by EK in 1974 [23].

#### 3.2. Upgrowth model

We use 5 years as period interval to calculate the upgrowth transition probability and this upgrowth model was also built by stepwise regression as follows:

$$P_{i+1,i} = 0.426 - 0.001 D_i^2 + 0.035 D_i - 0.009 \ln B_i + 0.0002 B_i^{1.5}$$

$$R^2 = 0.71 \quad (11)$$

The upgrowth model above did not contain the independent variable $N$ (the total number of trees in the stand), which indicated that the number of trees did not significantly affect the upgrowth of trees. Basal area of the forest stand, however, seems to have influence on upgrowth probability as it is an independent variable in this model.
3.3. Mortality model

The mortality models were built for three different diameter classes using the empirical model (9) which were listed in Table 1.

Table 1. Mortality model of small, medium and large diameter class

<table>
<thead>
<tr>
<th>Diameter class</th>
<th>Mortality model</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 and 12 cm (small)</td>
<td>$m_i = -7.448 \times 10^{-6} B^2+0.0005 B$</td>
<td>0.64</td>
</tr>
<tr>
<td>16, 20 and 24 cm (medium)</td>
<td>$m_i = -9.804 \times 10^{-6} B^2+0.00067 B-0.002$</td>
<td>0.55</td>
</tr>
<tr>
<td>more than 28 cm (large)</td>
<td>$m_i = 0.029 B - 6.781 \times 10^{-3} B^{1.6} + 9.498 \times 10^{-4} x_0^{0.3} - 2.916 \times 10^{-5} D_t^{0.25} - 0.626$</td>
<td>0.69</td>
</tr>
</tbody>
</table>

3.4. Transition matrix calculation

The transition matrix $G$ below was determined by combination of ingrowth, upgrowth and mortality model mentioned above and average basal area of the stands in initial investigation ($B=21.67 \, \text{m}^2 \cdot \text{ha}^{-1}$) as initial input value. The growth matrix $G$ was the average transition probabilities for each diameter class of stands with five years as period interval.

$$G = \begin{bmatrix}
0.2921 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.6344 & 0.1300 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.6947 & 0.1183 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.7224 & 0.2023 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.7185 & 0.2383 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.6823 & 0.3355 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.6142 & 0.4355 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.5145 & 0.5675 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.3825 & 0.7315 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2185 & 0.8275 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.8275 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.8308
\end{bmatrix}$$

Except for the diameter class 8 and 12 cm, with the increase of diameter class, the upgrowth probability gradually decreased, which dropped a broad range from 0.7224 to 0.1225 with mean upgrowth probability of 0.4969 (standard error of 0.2327). In contrast, the retention probability gradually increased from 0.1183 to 0.8308 with the mean value of 0.4764 (standard error of 0.2747).

3.5. The main code of FORTRAN program for building simulator

```fortran
DO i=1,n
   READ(24,*) b(i)
ENDDO
CLOSE(24)
c=0
DO i=1,n
   DO j=1,n
      c(i)=c(i)+a(i,j)*b(j)
   ENDDO
ENDO
```

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3.6. Model test

In order to scientifically and objectively evaluate the fitting effect, the number of trees five years ago was used to predict the number of trees five years later. The relative error for the total number of trees is +0.09%. The average relative error of number of trees is ±8.14% for each diameter class (Table 2). In addition, chi-square test was conducted to evaluate the fitting accuracy of models by using average number of trees of each diameter class for all independent sample plots which did not participate in the model establishment. The result showed that there was no significant difference in theoretical and actual number of trees in each diameter class ($\chi^2=1.48<\chi^2_{0.05}=16.92$). The simulation precision satisfied the requirements and models can be used to predict the growth dynamic of uneven-aged forests.

Table 2. Comparison between the theoretical and actual number of trees (Unit: N·ha$^{-1}$)

<table>
<thead>
<tr>
<th>Diameter class (cm)</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>24</th>
<th>28</th>
<th>32</th>
<th>36</th>
<th>40</th>
<th>≥44</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>318</td>
<td>281</td>
<td>217</td>
<td>141</td>
<td>89</td>
<td>52</td>
<td>25</td>
<td>22</td>
<td>7</td>
<td>3</td>
<td>1155</td>
</tr>
<tr>
<td>Theoretical</td>
<td>319</td>
<td>284</td>
<td>215</td>
<td>145</td>
<td>94</td>
<td>50</td>
<td>25</td>
<td>16</td>
<td>6</td>
<td>2</td>
<td>1156</td>
</tr>
<tr>
<td>Error (%)</td>
<td>+0.31</td>
<td>+1.07</td>
<td>-0.92</td>
<td>+2.84</td>
<td>+5.62</td>
<td>-3.85</td>
<td>0.00</td>
<td>-27.27</td>
<td>-14.29</td>
<td>-33.33</td>
<td>+0.09</td>
</tr>
</tbody>
</table>

3.7. Model application and illustrative example based on simulator

In 1987, the checking method was firstly introduced to China by Yu et al. So far, it has been only implemented in spruce-fir mixed forest in Changbai Mountain and a good effect of stand growth was achieved by the checking method [28]. The selection cutting intensity of checking method stands is less than or equal to 20% and the selection cutting cycle is from 5 to 10 years [29]. In this study, we used the simulator to predict forest dynamics with no management activities and with selection cutting systems, respectively. The 20% selection cutting intensity was chosen for projecting stand dynamics under selection cutting management systems because it is found to be the most suitable and representative selection cutting intensity around this region from long-term study by Yu et al [28]. The simulation results were illustrated in Table 3 and Table 4.

Table 3. Long-term prediction of stand growth under no any management activities

<table>
<thead>
<tr>
<th>Forecast period (year)</th>
<th>Number of trees (N·ha$^{-1}$)</th>
<th>Total basal area (m$^2$·ha$^{-1}$)</th>
<th>Total volume (m$^3$·ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>319</td>
<td>1156</td>
<td>23.7</td>
</tr>
<tr>
<td>10</td>
<td>111</td>
<td>933</td>
<td>25.5</td>
</tr>
<tr>
<td>15</td>
<td>67</td>
<td>823</td>
<td>28.1</td>
</tr>
<tr>
<td>20</td>
<td>37</td>
<td>734</td>
<td>30.3</td>
</tr>
<tr>
<td>25</td>
<td>31</td>
<td>679</td>
<td>34.3</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>634</td>
<td>37.7</td>
</tr>
<tr>
<td>35</td>
<td>18</td>
<td>594</td>
<td>42.0</td>
</tr>
<tr>
<td>40</td>
<td>14</td>
<td>559</td>
<td>45.1</td>
</tr>
<tr>
<td>45</td>
<td>13</td>
<td>529</td>
<td>46.0</td>
</tr>
</tbody>
</table>
Table 4. Growth prediction for stands under selection cutting system after 20 years

<table>
<thead>
<tr>
<th>Selection cutting time</th>
<th>Diameter class (cm)</th>
<th>Density (N·ha⁻¹)</th>
<th>B (m²·ha⁻¹)</th>
<th>V (m³·ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Initially</td>
<td>331</td>
<td>225</td>
<td>156</td>
<td>144</td>
</tr>
<tr>
<td>20 years later</td>
<td>125</td>
<td>175</td>
<td>135</td>
<td>94</td>
</tr>
</tbody>
</table>

The stand basal area and volume (volume of individual trees in diameter class i was estimated based on the one-parameter volume table for Jilin province) in the forest under selection cutting systems were more than forest without any management activities after 20 years growing period. Meanwhile, the total number of trees and large diameter class trees have increased.

4. Conclusion and future work

We established ingrowth, upgrowth, mortality and transition matrix model, respectively. Meanwhile, a simulator was developed by FORTRAN program to predict forest stand dynamics. These models were tested by chi-square test and no significant difference were observed between the actual and predicted number of trees in each diameter class, which indicated the efficiency of the simulator developed.

Using the simulator, we projected the forest dynamics with selection cutting management and with no management and found that the stand basal area and volume of the forest under selection cutting management were more than stand with no management activity which showed that the selection cutting promoted the stand growth.

As we know that different tree species varied in their growth rate resulting in different upgrowth and retention probabilities, in this study, however, we assumed that all tree species in the same diameter class share the same growth rate which is against biological realism and this assumption could cause biased estimation. For the further works, the models will be developed for each tree species. In addition, since lack of the continuous monitoring plots under selection cutting management systems, we employed the same simulator developed for forest under no management activities to predict the forest dynamics under selection cutting systems by simple decreasing the retention probabilities. As a result, biased estimation will also be induced and permanent plots of selection cutting should be separately established and monitored continuously for the further study of models.

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6. References


