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SIMULATION OF LIGHT REGIMES IN TYPICAL SUBALPINE FOREST SUCCESSION SERIES OF EASTERN TIBETAN PLATEAU

ABSTRACT: Natural regeneration of forest depends on the light regimes of floor. Point-based methods such as fisheye photo and radiometer can not provide a full panorama of light regime of heterogeneous forest stand. Eastern Tibetan Plateau is a major forest belt characteristic of diverse forest type and topographic differentiation. Understanding the trend of changes of light regime along succession series of forest may be helpful for the management of ecosystems. Fragmented forest patches due to tectonic activity and human intervention have made this prediction difficult. We use a spatially explicit forest stand light model (tRAYci) to simulate light distribution within forest in typical subalpine forest succession series of eastern Tibetan Plateau. Due to the spatial heterogeneity of tree distribution in the subalpine area, the forest stand can be approximated with a spatially explicit model of trees. Three typical subalpine forest stands (Sabina forest (SF), Fir forest (FF) and Birch forest (BF)) are selected in the eastern Tibetan Plateau. The dominant species are sabina (Sabina saltuaria (Rehd. et Wils.) Cheng), fir (Abies faxoniana Rehd. et Wils.) and birch (Betula platyphylla Suk.) for each stand and they are spatially clumped in distribution. They represent old growth coniferous forest (SF, 330 years old), coniferous-broadleaved forest (FF, 180 ys) and pioneer broadleaved forest (BF, 40 ys). The parameters of the three-dimensional model of trees are calibrated with field measurements. The simulated values are generally consistent with observed values of radiation measured by radiometers installed in these stands and values derived from fisheye photos. Test failures may be caused by the incomplete submodel of crown as a gap free one. Light regimes in old growth and pioneer forest are much more heterogeneous than intermediate stages of forest. Light regimes of these forests are also reflected by the composition of understory herb layers.

KEY WORDS: light regime, light distribution model, subalpine forest, eastern Tibetan Plateau.

1. INTRODUCTION

Light is the source of energy and ecophysiological signals for ecosystems (Monteith 1977; McMurtrie and Wolf 1983, Oker-Blom et al. 1991, Landsberg et al. 1997; Alton and North 2007). One of the dominant factors controlling the growth and development of forest is the penetration of solar radiation (Law et al. 2001, Hardy et al. 2004). Data of light distribution in forest can be used to estimate forest growth and recruitment which are important for forest regeneration. The progress in forest modeling makes it possible to estimate light distribution in a stand (Li and Strahler
However one major challenge in using such models is the modelling of canopy in heterogeneous forest. Brunner (1998) developed a radiation transfer model (tRAYci) based on spatially explicit 3D forest canopy model. This model uses forest inventory data and positioning data to calculate the light intensity at given point within forest. Light attenuation in the foliated crown space is estimated according to Beer’s law, with the extinction coefficient calculated from leaf area density (LAD). Compared with other spatially explicit canopy model, the tRAYci model has the advantage that it needs fewer parameters than others (MacFarlane et al. 2003, Gersonde et al. 2004), thus facilitating modelling of heterogeneous forest (Brunner and Nigh 2000). The tRAYci model uses Beer’s law to calculate light penetrated through leaf shells of crowns where the condition for homogeneous medium is met and suitable for the modelling of heterogeneous canopy.

In China, the subalpine forest belt lies in the eastern Tibetan Plateau, and this area is rich in biodiversity. Many kinds of forest exist due to abundant species and diverse habitat (Sichuan Vegetation Study Group 1980). Man-made disturbance and tectonic activities also have great influence on the succession regime of forest in this area (Li 1990). Pioneer, old-growth and intermediate stage forests grow in patches with different size. Current subalpine forests in eastern Tibetan Plateau are dominated by old-growth and pioneer forest (Li 1990, Taylor et al. 1996). Their canopies are often irregular. Mosaic gaps in different size and shape are present in the canopies. The distribution of more or less isolated crowns and varied weather conditions determine the radiation transfer under forest. In clear days, the daily course of radiation under forest mainly depends on the location of sun and architecture of crowns. On cloudy days, the sky diffuse radiation is the dominant source of energy input. The light regime in forest at a given point is an integration of the light from whole sky dome. Other light regimes can be modelled as a mixture of clear and cloudy days.

The subalpine area is an important region for the water conservation of eastern China, and the cutting of forests has been banned since 1998 when disastrous flooding was induced by over cutting. Restoration of forests in this area would be aided by data on its growth, and light data is an important source for estimating forest growth. Natural regeneration of forest depends on the light regimes of floor and point-based methods such as fisheye photo and radiometer cannot provide a full panorama of light regime of heterogeneous forest stand. Understanding the trend of changes of light regime along succession series of forest may be helpful for the management of ecosystems. Our aim is to test the ability of tRAYci model to modelling the fine scale light regimes of different succession series of subalpine forest and find the trend of light regimes along the series. The results are verified by observation data of radiometer and analysis of fisheye photos.

2. MATERIAL AND METHOD

2.1. Plot description

Study sites are located in Wanglang Nature Reserve of Sichuan, China. The three plots (ca. 0.075 ha for each) set up in 2001 are Sabina-Spruce forest (SF), Fir-broad leaved mixed forest (FF) and Birch forest (BF). The dominant species are Sabina (Sabina saltuaria (Rehd. et Wils.) Cheng), fir (Abies faxoniana Rehd. et Wils.) and birch (Betula platyphylla Suk.) for these stands, respectively. The three plots represent old growth coniferous forest (SF, 330 years old), coniferous-broadleaved forest (FF, 180 yrs) and pioneer broadleaved forest (BF, 40 yrs). Plot survey was conducted in July of 2002. The stand position and parameters of forest structure are listed in Table 1. The species composition and spatial distribution of trees are plotted in Fig. 1. The stand tree height and leaf area index (LAI) progressively increase with stand age. The gap fraction for each stand is inversely related to LAI. However, the distribution of trunk number has a pattern of unimodal along the succession series. The highest trunk number and sectional area of trunk occurred in stand FF. Stand FF also has the highest diversity of tree species. The spatial pattern of the domi-
Table 1. The basic characteristics of three subalpine stands in Wanglang Nature Reserve.

<table>
<thead>
<tr>
<th>Plot</th>
<th>SF (sabina forest)</th>
<th>FF (fir forest)</th>
<th>BF (birch forest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>32.90729°N</td>
<td>32.97928°N</td>
<td>32.95422°N</td>
</tr>
<tr>
<td></td>
<td>104.05292°E</td>
<td>104.08360°E</td>
<td>104.12622°E</td>
</tr>
<tr>
<td>Altitude (m)</td>
<td>2540</td>
<td>2620</td>
<td>3000</td>
</tr>
<tr>
<td>Aspect</td>
<td>75°</td>
<td>0°</td>
<td>190°</td>
</tr>
<tr>
<td>Slope</td>
<td>30°</td>
<td>0°</td>
<td>40°</td>
</tr>
<tr>
<td>Age (years)</td>
<td>330</td>
<td>180</td>
<td>40</td>
</tr>
<tr>
<td>Size (m²)</td>
<td>36 × 23</td>
<td>32 × 25</td>
<td>30 × 25</td>
</tr>
<tr>
<td>Dominant species</td>
<td><em>Sabina saltuaria + Picea purpurea</em></td>
<td><em>Abies faxoniana</em></td>
<td><em>Betula platyphylla</em></td>
</tr>
<tr>
<td>Trunk number</td>
<td>37</td>
<td>61</td>
<td>36</td>
</tr>
<tr>
<td>Tree height (m)</td>
<td>11.2 (± 4.4) – sabina</td>
<td>17.0 (± 5.4) – fir</td>
<td>11.7 (± 2.4) – birch</td>
</tr>
<tr>
<td>Sectional area of trunk (m²)</td>
<td>2.4</td>
<td>3.1</td>
<td>1.1</td>
</tr>
<tr>
<td>DBH (cm)</td>
<td>22.1 ± 14.4 – sabina</td>
<td>24.3 ± 7.7 – fir</td>
<td>13.3 ± 5.4</td>
</tr>
<tr>
<td>HBC (m)</td>
<td>3.8 ± 2.1 – sabina</td>
<td>5.7 ± 3.0 – fir</td>
<td>4.5 ± 1.3</td>
</tr>
<tr>
<td>Crown width (m)</td>
<td>3.0 ± 1.2</td>
<td>4.0 ± 4.0</td>
<td>4.7 ± 1.7</td>
</tr>
<tr>
<td>Crown height (m)</td>
<td>9.7 ± 6.8</td>
<td>10.9 ± 4.1</td>
<td>7.2 ± 2.4</td>
</tr>
<tr>
<td>Gap fraction</td>
<td>0.193 ± 0.011</td>
<td>0.273 ± 0.043</td>
<td>0.365 ± 0.037</td>
</tr>
<tr>
<td>LAI (m² m⁻²)</td>
<td>1.87</td>
<td>1.25</td>
<td>0.91</td>
</tr>
</tbody>
</table>

* Note: LAI=leaf area index; DBH=diameter at breast height; HBC=height below crown

Fig. 1. Spatial distribution of the trees in three stands. Plot SF (sabina forest) and BF (birch forest) are represented in 3D map as they are on slopes. Plot FF (fir forest) is represented in 2D map because of the flat ground. Position of radiometer is marked with big triangle. Species names are given after an arrow pointing to their specific symbols.
nant tree species is clumped. Spruce (*Picea purpurea* Mast.) is randomly distributed in stand SF and FF. The LAI was initially obtained from fisheye photo analysis and corrected later with architecture data of trees (Wang and Wang 2004). Four radiometers of global radiation (300–1 150 nm; SK01-D from Measurement Engineering Australia PTY LTD) were installed in each stand.

2.2. Tree measurements

Each tree with diameter at breast height (DBH) > 4 cm is labelled and measured with traditional forestry methods to obtain the height, DBH, crown width and crown height. Leaf area density (LAD) is measured by harvesting the leaves in crown with size of 0.5 m × 0.5 m × 0.5 m and measuring the leaf area with weight and specific leaf area. The scale leaves of Sabina are expressed as surface area of young branches (Wang and Wang 2004).

The three-dimensional coordinates of trees were determined as follows: a clinometer with a compass and range finder are used to obtain the polar coordinates of tree base. The polar coordinate (ρ, θ) parallel to the slope of a plot is then transformed into Cartesian coordinate (x, y) by equation 1. The y-axis points to the north and x-axis to the east.

\[
\begin{align*}
    x &= \rho \sin \theta \\
    y &= \rho \cos \theta 
\end{align*}
\]  

where ρ is distance from clinometer to the tree at height of clinometer and θ is azimuth of the tree with respect to the clinometer.

Rotate the y-axis clockwise on the plane of slope till it is in line with the aspect of slope (equation 2).

\[
\begin{align*}
    x' &= \cos \varphi \sin \varphi \times x \\
    y' &= -\sin \varphi \cos \varphi \times y 
\end{align*}
\]

where \( \varphi \) is aspect. The resulted coordinate is then rotated around x-axis till the z-axis points to the zenith (equation 3).

\[
\begin{align*}
    x'' &= x' \\
    y'' &= y' \cos \beta \\
    z'' &= y' \sin \beta 
\end{align*}
\]

where \( \beta \) is slope.

2.3. Input parameters for TRAYci model

Two kinds of input files are needed for tRAYci: (1) a tree list file is a list of parameters for trees, including serial number of trees, species, base location of trunks, tree height, height below crown (HBC), DBH and crown width. (2) a parameter input file contains plot latitude, aspect, slope, size, species, crown shape, leaf shell width, LAD, sky type, ray tracing model and simulation period. Light within forest is expressed as percent above canopy light (PACL). The LAD of each stand is set to 3 m² m⁻³ for conifers in SF, 2 m² m⁻³ and 1 m² m⁻³ for conifers and broadleaved trees in FF, respectively. The LAD of birch in BF is set to 1 m² m⁻³ too (Wang and Wang, 2004). The crowns of each tree are presented as a foliage shell, and the thickness of shell is set to 20% of crown radii. The shape of crowns is set as an ellipse.

The three dimensional structure of forest is constructed based on the location of tree base and inventory data of forest. Light transfer in forest is performed by discretization the three dimensional forest model into cubic grid cell with size of 0.5 × 0.5 × 0.5 m. At each node of the grid, a virtual ray tracer is placed. The ray tracer emits rays to the full sky dome and calculates the attenuation at each path. The percent ratio of the integrated light intensity at ray tracer to light intensity above canopy (PACL) is the final result.

The simulation period is set in growing season from May 11 to August 31 during which we have corresponding climate data at each stand. It rained 54 out of the 113 days. The daily radiation over this region is 198 ± 80 W m⁻² (mean ± standard deviation). Therefore we set these days in half for sunny and diffuse sky to mimic the period. The standard overcast sky model is used to simulate diffuse radiation. A light map of each stand is displayed as slices at height of
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1.5 m, 5.5 m, 10.5 m and 20.5 m (15.5 m for stand BF).

2.4. Hemisphere photography

A 8 mm 180° angular fisheye lens (Nikon LC-ER1; f = 2.8) screwed onto a Nikon Coolpix 950 digital camera is used to record the upright canopy image of stands. The camera was placed on top of a tripod with fish-eye lens levelled and rotated in line with the north-south direction of a compass. Eight photos are taken at position near radiometers and fixed points in each stand on overcast days. The photos are analyzed with software HemiView 2.1 (Delta-T Devices Ltd, UK).

2.5. Radiation measurements

There are four global radiation meters installed on stand FF. One is installed above forest canopy and the other three (SR1, SR2 and SR3) installed at height 1.5 m in the stand. All the four radiometers are installed at the height of 1.5 m in the stand BF and SF. Data logging time is 15 min. We use ratio of values of radiometers to compare the difference. Thus the ratio in stand FF is equal to PACL, while others are the ratio between understory radiometers.

3. RESULTS

3.1. Horizontal light profile

Along with the increase of height, the light level in stand FF gradually decreases to a minimum and then increases (Fig. 2). At height of 1.5 m, the 10% PACL area in the stand is about 2 m². This area increases to more than 100 m² at height of 5.5 m and then divided into several blocks at height of 10.5 m without obvious reduction of low light area (LLA). At height of 20.5m, the full light area spreads from surrounding and divides the low light area into several smaller ones (concentric circles). The gradient of light increases with the tree height.
Fig. 3. Light contour map of SF (sabine forest) at different height level in relation to percent about canopy light (PACL). Axis x and axis y are plot dimensions with axis y parallel to the direction of slope.

Fig. 4. Light contour map of BF (birch forest) at different height level in relation to percent above canopy light (PACL). Axis x and axis y are plot dimensions with axis y parallel to the direction of slope.
The variation of light profile in SF stand is similar to that of FF stand (Fig. 3). The difference is that the low light area occurred is much lower than FF. The number of LLAs initially increases with height and then decreases. The spatial distribution of LLA also shifts from the east to the northwest.

Stand BF has a higher transmittance than FF and SF. The 10% PACL area at 1.5 m height is only about 1 m² with three large LLAs. With the increase of height, these LLAs merge and shift to the north at height of 5.5 m and 10.5 m. The merged LLA finally splits into several small ones at height of 15.5 m. The southern part of the stand is a high light region. High gradient of light occurs at south edge of crowns (Fig. 4).

3.2. Simulation validation

According to the data collected during the simulated time, the observed PACL for stand FF is 9.2%, 5.7% and 6.7% for SR1 to SR3. The simulated PACL at the corresponding location is 7.8%, 9.6% and 20%. Except for SR3, the observed value and simulated result are similar (Table 2).

The maximum value of radiation in stand BF is observed in radiometer SR1 and is used as denominator of the ratio. The sum of radiation measured by SR2-SR4 is in the range of 66–78% of SR1. The simulated result for location at SR1 is 61% and 30–34% for locations of other radiometers. The observation data are slightly higher than those of simulation (Table 2).

The simulated results for SR1 to SR4 in stand SF are 32, 21, 24 and 38% respectively. However the observed ratio of SR2, SR3 and SR4 to SR1 is 202, 102 and 132%. The values at SR2 and SR3 deviate higher than the simulated ones (corresponding ratio of simulated PACL is 65, 75 and 118%) (Table 2).

The calculated PACL from fisheye photos of stand SF, FF and BF are 33% (±6), 42% (±8) and 56% (±4) respectively. And the model-simulated value for each stand is 30% (±9), 17% (±12) and 42% (±13) respectively. One-way ANOVA analysis shows that only stand SF is equal in PACL value ($P = 0.05$) calculated between the two methods. PACL from fisheye photos is generally larger than that from simulation model. The standard deviation calculated from fisheye photos is generally lower than that calculated from the model.

4. DISCUSSION

4.1. Effect of forest type on light distribution

Canopy structure greatly influences the light regime of forest (Brown and Parker 1994, Canham et al. 1994). The heterogeneity of forest means that the light level changes spatially in forest. Horizontal profile of light is influenced by stand composition, architecture and phenological phase of species (Canham et al. 1994, Cescatti 1998, Kato and Komiyama 2002). Crowns with strong attenuation of light cause the low light area. The LAD determines the ability of light attenuation by crowns (Bartelink 1998). Therefore the LAI, an integration of LAD along the crown, influences the light regime greatly (MacFarlane et al. 2003). By

<table>
<thead>
<tr>
<th>Stand</th>
<th>Radiometer</th>
<th>Simulated value (%)</th>
<th>Observed value (%)</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td>SR1/SR4</td>
<td>9.2</td>
<td>7.8</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>SR2/SR4</td>
<td>5.7</td>
<td>9.6</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>SR3/SR4</td>
<td>6.7</td>
<td>20</td>
<td>67</td>
</tr>
<tr>
<td>BF</td>
<td>SR2/SR1</td>
<td>49</td>
<td>66</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>SR3/SR1</td>
<td>54</td>
<td>70</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>SR4/SR1</td>
<td>56</td>
<td>78</td>
<td>28</td>
</tr>
<tr>
<td>SF</td>
<td>SR2/SR1</td>
<td>65</td>
<td>202</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>SR3/SR1</td>
<td>75</td>
<td>102</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>SR4/SR1</td>
<td>118</td>
<td>132</td>
<td>11</td>
</tr>
</tbody>
</table>

* Note: values for stand FF are expressed as PACL while others are ratio between understory radiometers.
selecting the growing season for the simulation we avoid the phase change in phenology, and the LAI is relatively stable for each stand during the simulation period.

In old growth forests, there are many gaps and some of them are quite large. The elevation angle of surrounding trees determines the depth of direct light down to a gap. A close and tall tree having a high elevation angle and thus a long shadow influences a wide area on its north part much more than a small tree. On the other hand, trees in the north part of a stand will have less influence on light than trees in the south. The spruce trees in old growth stand SF are generally taller than sabina trees. Their long shadows swipe through almost entire stand. The clumpy Sabina trees make several large areas of LLA. Light intensity is very heterogeneous due to many gaps. The mesic understory species *Oxalis corniculata* L. and *Fragaria orientalis* Lozinsk. dominate in the herb layer of stand SF. There is also a layer of mosses consisting of feathermoss (*Actinothuidium hookeri* (Mitt.) Broth. and *Hylocomium splendens* (Hedw.) B.S.G.) on the floor of forest, a typical element in old growth coniferous forest in eastern Tibetan Plateau (Wang et al. 2007).

The understory species indicate that the light level on the ground is moderate. The birch forest in stand BF is a pioneer community under secondary succession. The spatially clumpy distribution and the shrubby habit of birch create a relatively continuous canopy of their own (Wang and Wang 2004). The lower height of trees and the south-oriented slope reduce the length of tree shadows, while their ability to influence the light regime towards the north is restricted. Light-loving species such as *Deyeuxia scabrescens* (Griseb.) Munro ex Dutchie, *Origanum vulgare* L. and *Artemisia subdigita* Mattf. are present in this sunny stand, corresponding to the high level of light above ground on the north part. Shade tolerant species such as *Cimicifuga foetida* L. and *Cypripedium flavum* Hunt et Summerh. occur under the crowns.

The mixed canopy of stand FF (fir forest) can be divided into 2 layers by height. The top layer consists of conifers and poplar. Deciduous broadleaved trees form the lower layer. The leaf angle of lower layer of canopy is almost horizontal. The light intensity near the ground is quite low due to the high density of trees and double interception of the canopy layers. Shade tolerant species like *Impatiens noli-tangere*, *Impatiens dicentra*, *Corydalis dasyptera* and *Cacalia deltphylla* dominate in the herb layer.

The model-simulated light regime is generally consistent with the light at the ground level indicated by composition of the herb layer. Light regimes in the floor of stand FF is much more homogeneous than stand SF and BF. The prevalent low light level in the floor of FF may inhibit the regeneration of forest and enhance the self-thinning with the developing of forest. The broadleaved trees have a larger extent of influence on the light regimes on the floor than conifers. They can create broad area of low light area and promote shade tolerant species to grow. However, the height of conifers causes them to utilize light resource at higher position and gain advantage over broadleaved trees.

4.2. Validation and model structure

Model simulation, radiometer observations and fisheye photography results across the forest are partly confirmed by each other. The limited number of radiometers and fisheye photos in each stand cannot represent the whole situation of the stand, especially for the heterogeneous ones. Thus, the simulation model produces a comprehensive image of a stand. But there is a trade-off between accuracy and number of parameters for the model.

The crown model, as a geometric shell, does not include any gaps in tRAYci. But in reality crowns are full of gaps, which vary in size and shape. They are also not perfect ellipse. Light can penetrate through gaps to the ground, which may explain why some observed values are not consistent with the results of simulation. Gersonde et al. (2004) found that simplifying the crown representation in the tRAYci model to average values for species and canopy strata in Sierra Nevada mixed-conifer forests resulted in little reduction in model performance for the light regime near the floor and makes this model especially applicable by using inventory data.

The model tRAYci simulates the light distribution but not global radiation. Light
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spectrum coincides with that of photosynthetically active radiation (PAR, 400–700 nm). The published ratio of PAR to global radiation is about 0.45 (González and Calbó 2002). The ratio of global radiation will eliminate the common factor and is equal to PACL. The spectral difference will not influence the ratio of radiation. Reported changes in spectrum of light penetrating forest (Federer and Tanner 1966) will not substantially influence the general pattern of global radiation (de Castro 2000).

For the whole stand the light level varies more at outer part than inner portion of stand where fisheye photos are taken. The small standard deviation of light level derived from fisheye photo is probably caused by the biased sampling. This is especially evident in stand SF where many gaps are exist and sampling are preferred to points with good covering of canopies.

The clumping effect of leaves on branches results in an underestimation of LAI (Chen and Cihlar 1995, Cescatti 1998) and thus underestimation of LAD. The tRAYci model is sensitive to the LAD, which will change the performance greatly. Fisheye photograph derived parameters usually underestimate LAI and overestimate the light level penetrated into the canopy (Chen and Cihlar 1995). We use field sampled LAD of each species to avoid this trouble. However, the heterogeneous age class and location of branches/leaves sampled may cause spatial difference in estimation of LAD (Chen et al. 1997). Although the LAD is only an approximation for different species for this study, the simulated results for the three stands are generally consistent with the real situation. The observed values of radiation (taken from radiometers) in pioneer and old growth stands are not all coincided with the values simulated by model. The species composition of understory herb layer is a good indication of light regime (Leach and Givnish 1999), and supports the result of model simulation.

5. CONCLUSION

Although there are some drawbacks for the treatment of crowns, the spatially explicit model tRAYci can simulate the general pattern of light regime of subalpine forest in eastern Tibetan Plateau with relatively few stand parameters. The accuracy of this model depends on reasonable LAD measurement for tree species, weather conditions and inventory data of forest. Point failure is normal for the model due to the structure of crown model. tRAYci model can provide valuable information about the panorama of light regimes of a forest, which can help monitoring the process of growth and recruitment of forest.

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6. REFERENCES


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