S E S 2 0 1 1
Seventh Scientific Conference with International Participation
SPACE, ECOLOGY, SAFETY
29 November – 1 December 2011, Sofia, Bulgaria

LAI DEVELOPMENT IN MIXED FOREST INFERRED FROM MODIS LAI/FPAR DATA PRODUCT – CENTRAL RHODOPE MOUNTAINS

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Keywords: *Leaf Area Index(LAI), logistic model, MODIS LAI/FAPAR, deciduous-broadleaf forest, evergreen-coniferous forest, Central Rhodope mountains,*

Abstract : *A model of LAI development is presented based on MODIS LAI/FAPAR data product for the period 2003-2010, Central Rhodope mountains. The model describes both the period of leafing and the period of senescence and allows evaluation of basic parameters of the process of development of leaf area as: start of vegetation season, end of season, rates of leafing and senescence processes, LAI at any point of vegetation development. A method is proposed for evaluation of LAI_{max} and the time when LAI_{max} is reached.*

ИЗМЕНЕНИЕ НА ИНДЕКСЪТ НА ЛИСТНАТА ПЛОЩ В СМЕСЕНА ГОРА, ВЪЗ ОСНОВА НА ПРОДУКТА MODIS LAI/FPAR – ЦЕНТРАЛНИ РОДОПИ

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Ключови думи: *индекс на листната площ, логистичен модел, MODIS LAI/FPAR, листопадна широколистна гора, вечнозелена иглолистна гора, Централни Родопи*

Резюме: *В настоящата статия е разработен модел на развитието на индекса на листната площ(LAI) въз основа на MODIS LAI/FPAR data product в периода 2003-2010, Централни Родопи. Разработеният модел описва, както периода на разлистване, така и периода на листопад, като позволява оценката на основни параметри на процеса на развитие на листната площ, като: начало на периода на активна вегетация, край на периода на вегетация, скорост на натрупване на листна маса, скорост на процеса листопад, стойностите на LAI във всеки момент от развитието на растителната покривка. Предложен е метод за оценка на LAI_{max} и момента от време, в който се достига LAI_{max}.*

Introduction

Global climatic changes and changes in atmospheric composition lead to changes in spatial distribution of plant communities on earth and the change of recorded phenological events through time. LAI determines the exchange of fluxes of energy, mass (e.g., water and CO_2), and momentum between the surface and the planetary boundary layer. From a micrometeorological perspective [1] an increase in Leaf Area Index increases light interception and the source/sink strength for heat, water and CO_2 exchange.

LAI is defined as the one sided green leaf area per unit ground area in broadleaf canopies, or as the projected needle leaf area per unit ground area in needle canopies. The aims of the present work are: 1) to study spatial distribution and annual dynamics of the Leaf Area Index over a mixed forest in the Central Rhodope mountains, 2) to build a functional, deterministic type of model of LAI development during the greenup and the senescence periods of vegetation development and to apply it in order to define the key characteristics of leaf area development such as maximum rate of growth, maximum value of LAI, days of year when they are reached, etc..

Study area

The presented study covers a spot (42.0190N, 24.6849E; 42.0263N, 24.6751E), part of the Central Rhodope mountain forest, an area with temperate climate (characterized by a cold, damp winters and hot, dry summers). The average annual temperature varies between 6 and 11^{o}C. The annual temperature sums during the vegetation period are between 1200 and 2300^{o}C and the long-term average annual precipitations are between 700 до 1100mm.

The study area is located between 300 and 1800 m altitude. The lower elevations (300- 600m) are dominated by mixed deciduous forests *Quercus pubescens, Q. virgiliana, Carpinus betulus, Fr. excelsior L., Tilia, Juniperus oxycedrus*, while the higher elevations (over 700m) are dominated by *Fagus sylvatica, Pinus sylvestris and Picea*.

Materials and methods

image data retrieval and processing

This study is based on analysis of the LAI/FPAR (ESDT: MOD15A2) 8-day Composite dataset collected by the Moderate Resolution Imaging Spectroradiometer onboard of Aqua (EOS PM) satellite, NASA. Science Data Sets provided in the MYD15A2 include LAI, FPAR, a quality rating, and standard deviation for each variable [2], [3]. Quality control (QC) measures for the MOD15A2 product are produced at a tile and at a pixel level. At the tile level, these appear as a set of metadata. At the pixel level, quality control information is presented by 2 data layers (FparLai_QC and FparExtra_QC). Therefore users should take into account the QC layers of the LAI/FPAR product to select reliable retrievals.

algorithm description

(1) Data mining from the HDF(Hierarchical Data Format) [4] database for the studied area. As a result an yearly database of 45 images is formed containing the LAI data, measured by sensors over the studied area They are related to the 45 files containing images quality data at pixel level.
(2) Initial filtering of the data taking into account the quality control flags.
(3) Averaging Leaf Area Index over the image pixels and forming yearly LAI data sets for the 2003-2010 time range.
(4) Building a model of LAI development during the vegetation period.

LAI development model

We assume an additive model of LAI composition, i.e. the LAI time series are concerned as comprising three components: a seasonal component B(t) defined by the deciduous-broadleaf forest, evergreen-coniferous forest' and shrubs' component E(t), and an irregular (noise) component ε(t):

(1) $LAI(t)= B(t) + E(t) + \varepsilon(t)$

E(t) acts as a background component and it changes slightly over time. This component can be evaluated easily by analyzing the months in which $B(t) \approx 0$, late autumn and winter. The broadleaf component B(t), which has strong seasonal variations, has a significant contribution to development of Leaf Area Index.

Growth functions are widely applied in many branches of biological sciences. There are two types of models that can be used to describe the plant development during the vegetation cycle [5]. Empirical models are widely used and are essentially direct descriptions of observational data. The empirical models are not based on the understanding of the processes that rules the vegetation growth. They don't include any biological information, don't account for fundamental physical processes and laws, such as energy or mass conservation. The approach is very simple – to choose any curve that best fits the experimental data. To study the *LAI* development, another approach is used known as dynamic deterministic models that are concerned with the understanding of the mechanisms that rule the processes in plants or vegetation as a whole.

In this context here we use the logistic growth model to describe the Leaf Area Index behavior during the vegetation period. These types of models are related to the mechanisms that rule the processes in plants or vegetation as a whole. i.e. they are functional type models [5]. The logistic model foundations are the assumptions that the rate of change of the Leaf Area Index is proportional to the leaf area and depends on food resources of the environment and the microclimate at the time. This fact, together with moderate valuations, which the logistic model provides, should be taken into account when choosing a model describing the evolution of vegetation cover based on remote sensing measurements. The time course of Leaf Area Index is described by so-called growth function LAI = LAI(t), t- time. Thornley [5], formulate the basic criteria that the growth function has to satisfy: it should be derived from a differential equation for d(LAI)/dt; the parameters in this equation should be biologically meaningful, as substrate supply, environmental conditions, development rates and so on. To describe LAI development we have to propose that growth rate of LAI at the time moment t is proportional to the value of LAI at the same time t, growth rate is proportional to the amount of substrate S and growth is irreversible. The differential equation satisfying the assumptions above is

(2) $$\frac{d(LAI)}{dt} = k.(LAI).S$$

where k is constant and S is substrate level at time t. The equation (2) satisfies the initial conditions LAI (0) =LAI_0, S(0) = S_0 and is known as the logistic growth model. It is assumed that there is no net gain or loss from the system, i.e. LAI + S = LAI_0 + S_0 = LAI_f = const. Here LAI_f is final value of LAI approached as $t \to \infty$. At $t \to \infty$ all of the substrate is used and S (∞) → 0. Equation (2) is readily integrated and the solution is

(3) $$LAI = \frac{LAI_0.LAI_f}{LAI_0 + (LAI_f - LAI_0).\exp(-\mu.t)}$$

where μ = k.LAI_f. The coefficient μ is the specific growth rate during the early stages of plant growth when (LAI/LAI_f)<< 1. The key features of the logistic growth are [6]: *(i)* $\lim_{t\to\infty} LAI(t) = LAI_f$, i.e. LAI will ultimately reach its carrying capacity; *(ii)* The relative growth rate, declines linearly with increasing LAI. *(iii)* The Leaf Area Index (LAI) at the inflection point (where growth rate is maximum), LAI_{inf}, is exactly half the carrying capacity:

(4) $$LAI_{\inf} = \frac{1}{2} LAI_f$$, which occurs at $$t_{\inf} = \frac{1}{\mu}\ln\left(\frac{LAI_f - LAI_0}{LAI_0}\right)$$

The parameters L_0, L_f, μ of the fitting function LAI(t) = LAI (t; L_0, L_f, μ) to measured data points (t_i, LAI_i) are found minimizing the sum of the weighted squares of the errors (or weighted residuals) between the measured data $LAI_i(t_i)$ and the values of the curve-fit function LAI (t_i; L_0, L_f, μ):

(5) $$\frac{1}{2}\sum_{i=1}^{m}\left[\frac{LAI(t_i;L_0,L_f,\mu) - LAI_i(t_i)}{\varpi_i}\right]^2 = \min$$

where ω_i is a measure of the error in measurement $LAI_i(t_i)$. The function LAI (t; L_0, L_f, μ) is nonlinear in the model parameters L_0, L_f and μ and there aren't parameters constraints. Therefore the minimization (5) is done using the Levenberg-Marquardt method [7].

Two scenarios of LAI development are studied:

average year scenario:

Let L_{mn} is Leaf Area Index measured by satellite sensor during the m-th time interval of the n-th year. Than we composed an averaged year data set LAI_{avrg}. The elements of LAI_{avrg} data set are:

$$LAI_{avrg} = \left\{\overline{L_m} : \overline{L_1}, \overline{L_2}, ..., \overline{L_N}\right\} \text{ where, } \overline{L_m} = \frac{1}{N}\sum_{n=1}^{N} L_{mn}$$

upper envelop scenario:

The other data set we have studied is the upper envelope data set $LAI_{UpEnvlp}$.

$LAI_{UpEnvlp}$ = {$L_{m;\,max}$: $L_{1\,max}$, $L_{9;\,m}$, . . ., $L_{361;\,m}$}

where, $L_{m;\,max}$ = max{ $L_{m;1}$, $L_{m;\,2}$, ..., $L_{m;\,N}$ }

The upper envelope scenario is closer to field data because account for data quality more precisely and therefore it is preferable in the analysis of remote sensing data.

Results and Discussion

The dynamics of vegetation cover can be investigated using frequency distributions of Leaf Area Index. At the beginning and end of vegetation period (see DOY 89 and DOY 273- Figure 1) the contribution of evergreen plants stands out. These are mainly isolated stretches of pine forests, in the higher parts of mountains. In the lower mountain evergreen areas are formed by juniper bushes.

For dates presented DOY 89 and DOY 273 (Figure 1), the study area is snow-free and the vegetation process in deciduous-broadleaf forests is closed and therefore the evergreen-coniferous vegetation contribution in LAI is dominant (E(t) is in the range of 1-2, B(t) ≈ 0). The process of quick unfolding of deciduous forest begins in May (see DOY 153). At the beginning, the process comprises oak, hornbeam, ash and tilia mixed forest at lower altitudes, and later comprises the dominant beech forest ecosystem at altitudes of over 500m. In the middle of the vegetation period (see DOY 201) the distribution of LAI is uniform and ranges from 1 to 5.

Evergreen-coniferous forest and ahrubs contribution.

The forest in the studied area is a mixed one, dominated by deciduous species beech, oak and hornbeam, but in the higher altitudes over 1000 to 1200 m there are evergreen coniferous forests. This requires assessment of the coniferous forest contribution E(t) to the spatially averaged Leaf Area Index. The stand-out of evergreen vegetation in remote sensing observations is strongest in late autumn and winter, at the end of November, December, January, February to mid-March. During this period the leaves in deciduous forests have fallen and B(t) ≈ 0. Major difficulty is the presence of significant cloud and snow covers, which affect the quality of remote sensing data. LAI during this period does not change since the processes of development in evergreen-coniferous forests are stopped and LAI ≈ E(t).

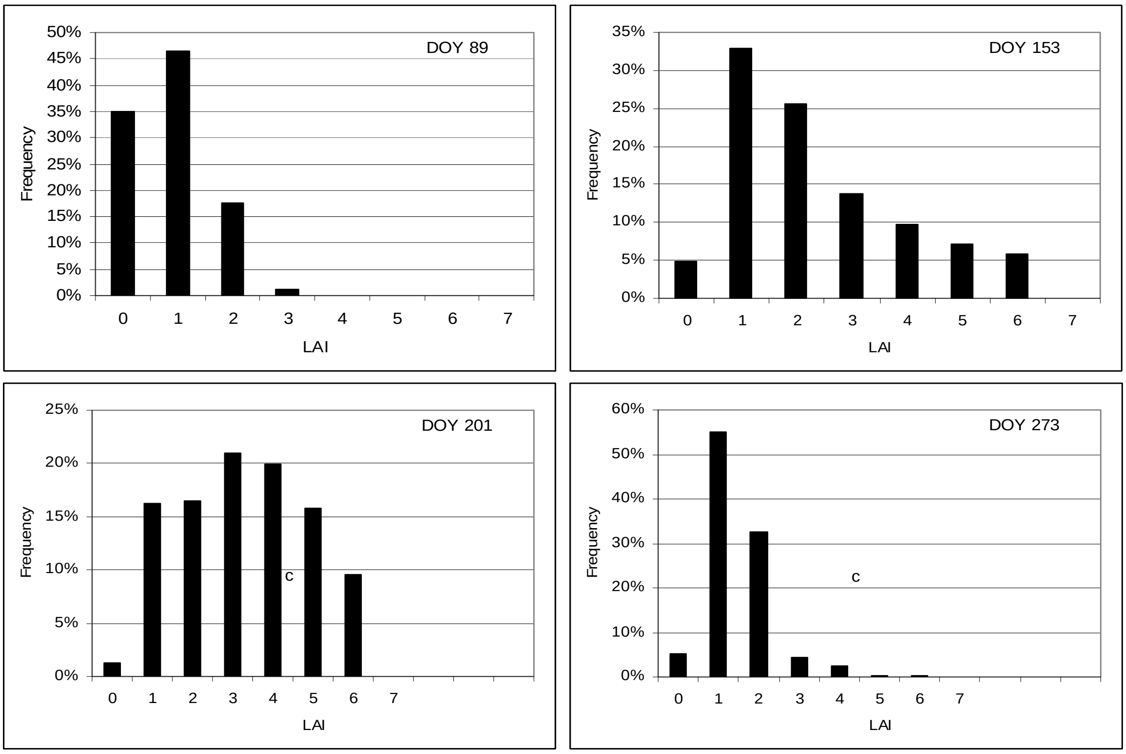
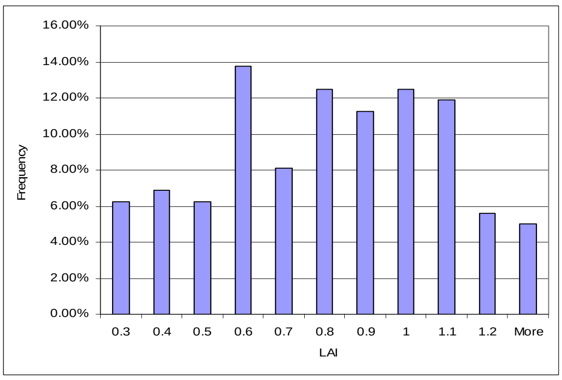


Fig. 1: Frequency distributions of Leaf Area Index at the beginning (DOY 89 and DOY 153), middle (DOY 201) and the end (DOY 273) of vegetation period. Mixed forest.



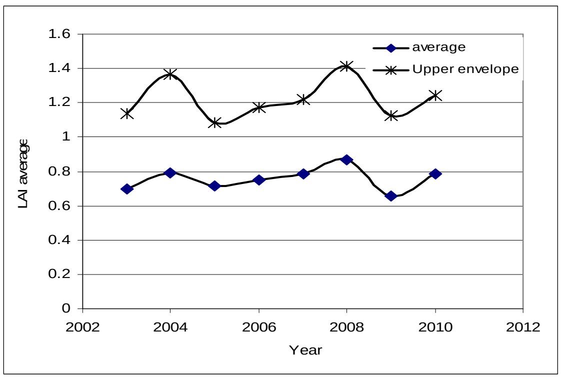


Fig. 2

Fig. 3

Fig. 2: Frequency distribution of LAI for evergreen canopy, (number of days with LAI) during the dormancy periods of the years 2003- 2010.

Fig. 3: LAI annual average development for evergreen canopy in the studied region. Upper envelope is annual LAI_{max}, over the dormancy periods- end of November, December, January, February, March).

As shown in Figure 2, during the dormancy period, different values of E(t) reflect the cloud and snow covers' influence on the quality of vegetation index data. To exclude the errors caused by snow cover presence, cloudy days and technical uncertainties, E(t) upper envelope data sets should be used (Figure 3). As one can see the E(t) upper envelope values are between 1.2 and 1.4. The average E(t) during the studied period 2003-2009 is 0.76, which is 30% lower than the upper envelope estimation of E(t) = 1.22. There are two pronounced declines in the E(t) upper envelope and E(t) averaged data sets, during 2004-2005 and 2008-2009 periods. The reasons should be further specified but probably are related to the climatic anomalies and ongoing deforestation in the studied area during the years.

Deciduous-broadleaf forestt.

After having assessed the contribution of evergreen trees to Leaf Area Index E(t), one can study the LAI produced by deciduous trees B(t) (see equation (1)) as:

(6) $$B(t) = LAI(t) – E(t) + \varepsilon(t)$$

There are two possible scenarios about E(t) in equation (6): (i) E(t) = average evergreen LAI during the dormancy period; (ii) E(t) = upper enveloped data during the dormancy period. The upper enveloped E(t) data set is used in (6). The parameters of the logistic model (2) for broad-leaf component of Leaf Area Index B(t) are presented in Table 1 (greenup period) and Table 2 (senescence period).

Table 1: Logistic model fitting parameters during the greenup period of vegetation development. (*Avrg- average year scenario; UpEnvlp- upper envelope scenario*)

Year	L_0	L_f	$\lvert\mu\rvert$	t_{inf}	LAI_{inf}	R^2
2003	0.0039	2.954	0.05192	127	1.477	0.965
2004	0.0058	3.341	0.04251	149	1.670	0.949
2005	0.0038	3.029	0.04442	150	1.514	0.928
2006	0.0070	2.923	0.04183	144	1.462	0.944
2007	0.0132	3.270	0.03831	144	1.635	0.936
2008	0.0071	3.015	0.04336	140	1.507	0.970
2009	0.0049	3.231	0.04254	153	1.615	0.921
2010	0.0332	3.116	0.02708	167	1.558	0.939
Avrg	0.0021	2.577	0.05178	137	1.288	0.987
UpEnvlp	0.0006	3.036	0.06632	129	1.518	0.987

Table 2: Logistic model fitting parameters during the senescence period of vegetation development,

Year	L_0	L_f	$\lvert\mu\rvert$	t_{inf}	LAI_{inf}	R^2
2003	0.0814	3.058	0.02969	239	1.529	0.945
2004	0.1304	3.351	0.02806	246	1.676	0.913
2005	0.0328	2.784	0.04136	253	1.392	0.905
2006	0.0758	2.859	0.03492	257	1.429	0.876
2007	0.0553	3.136	0.03869	256	1.568	0.892
2008	0.0237	2.977	0.04312	248	1.488	0.924
2009	0.0782	3.192	0.03237	246	1.596	0.891
2010	0.1590	2.913	0.02669	253	1.456	0.790
Avrg	0.0195	2.579	0.04970	262	1.289	0.987
UpEnvlp	0.0180	3.008	0.05604	269	1.504	0.989

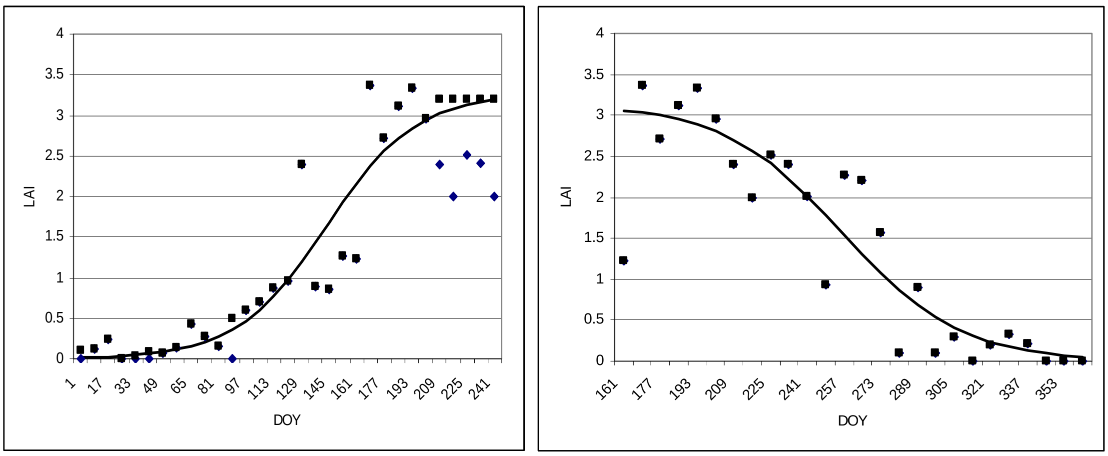


Fig. 4: LAI development over 2007, logistic model (continuous line) and measured data(dots).

The maximum value of Leaf Area Index L_f of deciduous forest, obtained after parameterization of the greenup (spring) logistic model varies from 2.92 to 3.34, while the assessment obtained after parameterization of the senescence (autumn) logistic model varies from 2.78 to 3.5. However, these differences are not statistically significant (α = 0.05). The rate of change of leaf area during the greenup period μ_{spring} is greater than that during the senescence μ_{autumn}: $\mu_{spring} > \mu_{autumn}$, at significance level α = 0.05, which reflects the asymmetry in the process of annual change in LAI. In spring, the rate of accumulation of LAI reaches a maximum value around the 147 DOY, while the maximum rate of senescence is reached around 250 DOY (see t_{inf} , Table 1 and Table 2). The logistic model describes better the process of accumulation of biomass (R^2 = 0.94, averaged over the studied period 2003-2010), compared with the senescence process (R^2 =0.89). This is due to the fact, that the logistic model is a `growth type' model, which essentially ignores specificity of the senescence process.

Maximum LAI problem

The local model functions describe *LAI* data very well in spring and autumn separately, but at the limbs, however, the fits are less good. In the logistic model L_f is the value of *LAI* at $t \to \infty$. So it is not possible, based on the logistic model to determine the time when *LAI* reaches the maximum value L_f. Detailed analysis shows that, the rate of development μ of Leaf Area Index near the maximum is a decreasing linear function with time and changes its sign from plus to minus. So t_{max} can be defined as the moment of time when the growth rate becomes zero:

(7) t_{max}: $\mu(t_{max}) = 0.$

The results of linear regression analysis over the measured data within the time interval [105, 281] DOY are presented in Table 3. During the studied period 2003-2010, the average t_{max}, the day when LAI reaches a maximum value, is 202 DOY (confidence level (95.0%) = 6.6). The average value of the maximum measured Leaf Area Index LAI_{max} over the period is 3.27 and varies slightly. With regard to t_{max}, anomalous years are 2005, 2006 and 2010. In 2005 and 2010 t_{max} shifted by 7 and 11 days ahead of the average date for the period, while in 2006 t_{max} was delayed by 23 days. It should be noted that during the anomalous years, productivity of the ecosystem did not change, the range of LAI during the period is 0.5.

Table 3: The day of the year (t_{max}) when *LAI* reaches the maximum value. LAI_{max} – measured maximum LAI. *Avrg* and *UpEnvlp* are results from average year and upper envelope scenarios data sets analyses.

Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Avrg**	**UpEnvlp**
t_{max}	203.9	203.4	195.2	225	202.3	206.6	198.2	191.4	197	197.9
LAI_{max}	3.188	3.539	3.133	3.509	3.365	3.229	3.195	3.007	2.654	3.278

Conclusions

The presented model describes well the development of leaf area in the Central Rhodope mountains, and can be used to explore: phenology of vegetation cover, productivity of the ecosystem, health status of the ecosystem in terms of diseases and insect pests.

To clarify anomalies during the period, it is necessary to investigate the influence of climatic factors on the productivity of the ecosystem and the effect of the observed processes of deforestation in the region in recent years.

Acknowledgements

I would like to thank the various MODIS software development and support teams for the production and distribution of the MODIS data, and making available them to the scientific community.

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