Mathematical models for determining the boundaries of forest areas unstable to the appearance of insects using satellite data (MODIS)

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Abstract. The proposed approach allows us to evaluate the response of forest stands to local weather changes and resistance to insect attack without using data from weather stations, sometimes located far from experimental forest areas. All raw data were obtained during the season using remote sensing data (MODIS / AQUA). The ability to pre-determine decrease and loss of forest stands resistance to possible insect attacks can be extremely important for solving the tasks of forest-entomological monitoring and calculating the risk of forest insect’s outbreaks.

1. Introduction
Outbreaks of forest insect pests dramatically affect the state of the ecosystem and lead to negative consequences for the local economy. Such outbreaks result in significant economic losses. Understanding the factors influencing the development and spread of an outbreak is critical to forest management [1,7].

Usually, insect population growth is described using population models based on laboratory and field data [3,8,1]. Successful pest control requires an integrated approach to the analysis of insect population outbreaks. Such models should describe population growth and its distribution as a function of environmental regulatory factors, landscape topology, and interactions of fodder trees with pests. Therefore, the assessment of the current state and resistance of forest stands to insect attack is extremely important in forest management. In this case, it is necessary to obtain estimates of change in the state of the forest in advance, before the impact of insects.

A change in the state of stands is a necessary, although sometimes an insufficient, condition for a subsequent attack by pests. The territories where entomological monitoring is carried out can be significantly reduced by assessing the loss of stability of the stand before the outbreak. This would allow to start protecting forest stands from insect attacks in time. However, regular ground-based observations of all stands and an assessment of their resistance to insects are technically impossible across the large territories of Siberian taiga forests. The only valid way to analyze forest stands conditions across large areas is to use remote sensing data.
Remote sensing is widely used in mapping spatial dynamics of insect outbreaks [4,9]. However, the main purpose of such studies is to assess the damage caused by the outbreak and calculate the area of loss. Attempts to use remote sensing data to assess the state (and, most importantly, resistance) of forest stands to external impacts do not lead to success [11,10,7]. The development of such methods is necessary. It would be desirable to identify the areas of future insect outbreaks at least one or two seasons before the damage. This can lead to improved outbreak forecasting and the development of effective preventive actions to reduce losses.

In this paper, we consider an approach to the analysis of remote sensing data of forest territories, which permits to obtain estimates of the state and resistance of forest stands to insect attack in advance. We propose to use the calculated parameters of the NDVI (Normalized Difference Vegetation Index) susceptibility to changes in the temperature of the underlying surface as an indicator of the state of forest stands. Both indicators were obtained during the season using remote sensing data (MODIS / AQUA).

2. Study area
Forest stands were located on the territory of the Yenisei region of the Krasnoyarsk Territory, Russia. The analysis was carried out for the 10 test plots that have been damaged by Siberian silkworm caterpillars (Dendrolimus sibiricus Tschet.) since 2016 and for the 10 test plots where the trees have not been damaged. The location of the test plots is shown in figure 1.

![Figure 1. Experimental areas across center of Siberian silkmoth outbreak (Krasnoyarsk region near the village Ust-Pit). Dark dots - stands damaged by insect, light dots - control stands (Source: the Krasnoyarsk Forest Protection Center).](image)

3. Research methods
To assess the state of forest stands, MODIS/AQUA remote sensing data were used. Calculated NDVI (product MYD09Q1, channels b01, b02) and the temperature of the underlying surface T (product MOD11A1, channel LST_Day) were used as parameters. The absolute values of NDVI strongly depend on the season and type of vegetation, and it is rather difficult to assess the state and stability of stands using these absolute indicators.

The forest can be considered as a system in which changes in the output variable (NDVI) depend on the input variable (temperature T) with some delay. In this case, the susceptibility of NDVI changes to temperature change can be used to assess the state of forest stands. To calculate the susceptibility, we can write the integral equation relating the changes in ΔNDVI and temperature ΔT:
\[ \Delta \text{NDVI}(t) = \int_{0}^{t} h(\tau) \cdot \Delta T(t - \tau) d\tau \]  

(1)

where \( \Delta \text{NDVI}(t) \) is the change in the NDVI value during the season, \( \Delta T(t) \) is the change in the temperature of the underlying surface during the season, \( h(\tau) \) is the response function (the pulse transition function of the system characterizing the susceptibility of the NDVI value to temperature).

The value \( h(\tau) \) characterizes the dynamic connection existing between the input \( T(t) \) and the output \( \text{NDVI}(t) \), and this parameter can be used as an indicator of the stands’ state. If \( h(\tau) \to 0 \), a change of environmental temperature does not affect the change of NDVI. For small values of \( h(\tau) \), the NDVI value is resistant to temperature.

Let us try to solve the inverse problem: we will find the response functions \( h(\tau) \) from the known values of the input and output (NDVI and \( T \)). A relationship equation between the cross-correlation function of the input and output of the system and the autocorrelation function of the input can be written [5,2] in the following way:

\[ \Phi(\Delta \text{NDVI}, T) = \int_{0}^{t} h(\tau) \cdot \Phi(\Delta T(t - \tau)) d\tau \]  

(2)

where \( \Phi_{\text{IO}}(\omega) \) is a Fourier transform of the cross-correlation function \( \Phi(\Delta \text{NDVI}, T) \), \( \Phi_{I} \) - Fourier transform of the autocorrelation function of the input \( \Phi(\Delta T(t - \tau)) \), \( H(\omega) \) - Fourier transform of the response function \( h(\tau) \).

After the Fourier transform (2) we get:

\[ \Phi_{\text{IO}}(\omega) = H(\omega) \cdot \Phi_{I}(\omega) \]  

(3)

From (3) we can calculate the Fourier transform of the response function:

\[ H(\omega) = \frac{\Phi_{\text{IO}}(\omega)}{\Phi_{I}(\omega)} \]  

(4)

Thus, by calculating cross- and autocorrelation functions, we can find the Fourier transform of the response function and estimate the dynamic relationship between the change in the temperature of the underlying surface and change in NDVI.

The calculation of correlation functions is correct only if the functions are stationary and have the integrability order \( d=0 \). However, both the NDVI(t) time series and the T(t) time series have seasonal trends. For such series the integrability is \( d>0 \). The usual method for eliminating the trends of time series is the transition from the series \{y\} with integrability \( d>0 \) to the series of the first differences \{\Delta y\}. After the transition from the initial series NDVI(t) and T(t) to the series of the first differences, the stationarity of the obtained series is checked using the Dickey - Fuller test [12]. If the resulting series does not satisfy the stationarity test, we can proceed to the series of second differences, etc.

The following algorithm can be proposed to assess the state of the stand:

- According to MODIS data, for the territory with vegetation uniform in type and species composition (coniferous or deciduous forest, meadow, steppe, etc.), NDVI(t) and T(t) values for entire season are found;
- The series of the first differences NDVI and T are calculated;
- According to Dickey - Fuller test, a check is made for stationarity of time series; if series do not satisfy the Dickey - Fuller test, the calculation of first differences is repeated until it satisfies the Dickey - Fuller test;
- Filtering of the obtained time series is performed, and high-frequency outliers of the values of the series are deleted;
The cross-correlation function $\Phi(\Delta NDVI, T)$ between the input $\Delta T$ and the output $\Delta NDVI$ and the autocorrelation function $\Phi(\Delta T(t-\tau))$ of the input are calculated;

The Fourier transforms of the auto- and cross-correlation functions are calculated;

According to (4), the spectral functions are recalculated as an indicator of the stand’s state.

4. Results and discussion
Using MODIS/AQUA data, we constructed the series of seasonal dynamics of NDVI and the temperature of the underlying surface for 2003-2018 for all sample plots. For the time series $NDVI(t)$ and $T(t)$, seasonal trends are present. Therefore, to calculate the correlation functions, a transition was made to the series of the first differences. For such series, the Dickey - Fuller test indicates the absence of a trend. This allows us to calculate cross- and autocorrelation functions and calculate spectral response function from Fourier transform (figure 2).

The spectral response functions were calculated from the seasonal data of NDVI (t) and T (t) in 2003-2018 for the 10 test plots damaged in 2016 by the Siberian silkworm and 10 control intact test plots. To compare the spectral response functions of damaged and undamaged test areas, the response function was presented in the form of three numbers characterizing the powers of the low-frequency components of the spectrum ($0 \leq f_1 \leq 0.09$), power at medium frequencies ($0.2 \leq f_2 \leq 0.3$), and power at high frequencies ($f_3 \geq 0.43$). After that, for all 3 vectors of all test areas, the main components were calculated. Further, the data for damaged and undamaged sample plots were presented in the planes of the two principal components F1 and F2, describing 80-90% of the total dispersion (figure 3).

![Figure 2. Spectral response function.](image)

![Figure 3. Integral characteristics of the response function (2014 - 2015).](image)
To separate the characteristics of damaged and undamaged sample plots, linear discriminant analysis methods were used. At the same time, a comparative analysis of the possibility of diagnosis was carried out for spectral response function and parameters of the annual NDVI curve. For each diagnostic method, estimates of diagnostic errors of the first and second kind were obtained (table 1).

Table 1. Comparative assessment of diagnostics quality for two different methods.

| forecast errors | 2014 parameters of the annual NDVI curve | spectral response function NDVI(T) | 2015 parameters of the annual NDVI curve | spectral response function NDVI(T) |
|-----------------|------------------------------------------|-----------------------------------|------------------------------------------|-----------------------------------|
| 1 kind error - missed goal | 40% | 20% | 20% | 10% |
| 2 kind error - false alarm | 30% | 40% | 40% | 10% |
| total error | 35% | 30% | 30% | 10% |

As it follows from table 1, the use of response functions can significantly improve the quality of diagnostics of the state of stands at least a year before the damage by insects.

5. Conclusion

We estimate the average susceptibility of trees to temperature changes during the growing season, using the response functions to assess the current state of tree stands. This approach is widely used in neurophysiology and the theory of automatic control. This approach seems to be also promising in forest ecology. It contributes to evaluating the response of trees in the stands to local weather changes without using data from weather stations, sometimes located far from experimental forest plots. The ability to pre-determine decrease and loss of forest stands resistance to possible insect attacks can be extremely important for solving the tasks of forest-entomological monitoring and calculating the risk of forest insects’ outbreaks.

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