Possibilities of near real-time forest cover damage estimation based on fires radiative power data

D V Lozin, I V Balashov and E A Loupian
Dep.56, Space Research Institute of the Russian Academy of Sciences, 84/32 Profsoyuznaya Street, Moscow 117997, Russian Federation

*Corresponding e-mail: smis@smis.iki.rssi.ru

Abstract. The paper proposes a solution to the problem of operational assessment of forest cover damage based on the fire combustion intensity data. Approaches to the assessment of the considered phenomena are presented. An algorithm for comparing data to study the relationship between them is described. The results of such a comparison are discussed, and on that basis, a method is proposed for the rapid assessment of the degree the forest cover is damaged by fires. The integral estimates of the dead forest areas obtained using the described methodology throughout the country are compared with the corresponding actual values. Summing up the results of the work done, the effectiveness of the developed method is evaluated.

1. Introduction
At present, satellite monitoring makes it possible to obtain reliable estimates of a whole number of characteristics of the earth’s surface for solving various problems. The assessment of various forest coating characteristics is one of the pressing and timely trends. Some of those characteristics include the assessment of forest coating damage caused by wildfires impact, among other things. Such assessments, in particular, could be performed by analyzing the series of burnt-out places observation. In order to perform such estimates, the time-difference observation series are required, so they can be obtained with a considerable delay after the fires are put out. At the same time, on-line assessments of expected damages are of interest, too. They could be potentially performed by analyzing the combustion intensity of a particular fire. This paper considers the possibility of using combustion intensity information [1] to make such estimates. The relationship between fire radiative power (FRP) and the degree of damage to various types of woods is explored in this paper as well as the option of the method for rapid assessing the degree of damage to the forest coating by fires.

2. Methods and Materials
2.1. Features of the FRP assessment used
Earth Science Data Systems (ESDS) provides an open data burst Collection 6 MODIS Active Fire / Hotspot Data (MCD14DL) [2] - observation archive of active fires throughout the planet since 2000. This product is a set of information of thermally active pixels recorded by the MODIS spectroradiometer. In particular, its FRP calculation is automated for each pixel. Collection 6 uses the method described by Worcester, Zhukov and Oertel [3, 4], according to which the FRP is approximated by the formula
\[
FRP \approx \frac{A_{\text{pix}} \sigma}{\alpha \tau_4} (L_4 - \overline{L}_4),
\]

where, \(L_4\) stands for the energy brightness of a thermally active pixel (target) in channel 21 of the MODIS radiometer \(\lambda \approx 4 \ \mu \text{m}\), \(\overline{L}_4\) - for the background energy brightness in the same spectral range, \(A_{\text{pix}}\) - for the MODIS pixel area (which varies as a function of the scanning angle), \(\sigma\) - for the Stefan-Boltzmann constant, \((5.6704 \times 10^{-8} \ W \ m^{-2} K^{-4})\), \(\tau_4\) - for the MODIS channel 21 transmission coefficient in the atmosphere and \(\alpha\) - for the empirical constant depending on the device. For MODIS \(\alpha = 3.0 \times 10^{-9} W \ m^{-2} sr^{-1} \mu m^{-1} K^{-4}\). \(\tau_4\) is simply assigned a value of 1 and it is included in the formula for correct atmospheric correction in the next approximation.

In Collection 6, FRP is linearly dependent on the pixel area, reflecting in fact the integral value of the radiation power of the site. Thus, it is incorrect to compare FRP pixels of different sizes directly as values of the heat radiation power. In this regard, for further research, the FRP value normalized to the area of the observed pixel was used in the paper (hereinafter, this value is called FRPS).

### 2.2. Features of the data used on post-fire damage

As a characteristic of forest damage, the average weighted condition category (SCS) is often used, calculated as follows:

\[
SCS = \frac{\sum_{i=1}^{4} K_i \tau_i + 5 \sum_{i=5}^{6} K_i}{\sum_{i=1}^{6} K_i},
\]

where, \(K_i\) stands for the number of trees of the \(i\)-th category of tree condition according to the forest pathological classification, including the assessment of defoliation and discoloration degree of crowns. Traditionally, the following upper boundaries of SCS values intervals are established to classify the plantation condition categories: 1.5 - healthy plantation; 2.5 - weakened; 3.5 - heavily weakened; 4.5 - drying up. Plantations with an average weighted condition category above 4.5 are considered dead.

A fire-induced decrease of the chlorophyll content and moisture content in woody plants results in decreasing their reflectivity in the visible and near-IR regions of the spectrum, as well as in its increasing in the mid-IR region [5]. Earlier studies [6] have shown that the forests’ SCS value can be estimated remotely thanks to its being close to linear relationship with the normalized multi-time difference of the short-wave vegetation index RdSWVI [7], determined from satellite data as follows:

\[
\text{RdSWVI} = \frac{\text{SWVI}_{\text{pre}} - \text{SWVI}_{\text{post}}}{\sqrt{\text{SWVI}_{\text{pre}}^2 + T}},
\]

\[
\text{SWVI} = \frac{R_{\text{air}} - R_{\text{swir}}}{R_{\text{air}} + R_{\text{swir}}},
\]

where, \(R_{\text{air}}\) and \(R_{\text{swir}}\) stand for the values of the surface reflection coefficient in the near and mid-IR wavelength ranges, respectively, \(\text{SWVI}_{\text{pre}}\) - for the index value obtained from the image on a given date in the year preceding the fire, and \(\text{SWVI}_{\text{post}}\) - for the index value after exposure to fire. At the same time, the forests’ SCS values are estimated on the basis of RdSWVI values as stated in the following equation:

\[
SCS = a \times \text{RdSWVI} + b,
\]

where, the \(a\) and \(b\) coefficients are determined experimentally on the basis of a joint analysis of satellite observation data and ground-based forest pathological surveys.

### 2.3. Data used

As the initial FRP data, a homogeneous data series on fires and hot spots of the ICU IKI-Monitoring [8] was used. The said series had been formed on the basis of the Collection 6 MODIS Active Fire / Hotspot Data (MCD14DL) product. The data in the format convenient for analysis cover the territory of the Russian Federation from 2001 to the present and are annotated according to the maps of the territory types formed by the SRI RAS for each year [9]. As noted above, the FRPS value was used.
In order to compare forest damage data with the FRPS information, a number of data covering the territory of the Russian Federation from 2012 to 2019 was used, obtained with the method for assessing the degree of forest damage by fires based on MODIS satellite data developed at IKI RAS [10]. The data correspond to damage polygons indicating the date of determination and the extent of forest damage. The degree of damage is determined by one of five classes of the average weighted condition category (SCS): the first class stands for healthy plantations, the second one for weakened, the third one for heavily weakened, the fourth one for drying up, the fifth one for dead.

2.4. Method of FRP and damage data comparison

The problem of finding the relationship between the intensity of fire burning and post-fire damage, that was posed in the paper, requires the development of a method for correct matching of the existing initial FRP data of forest fires and the average weighted forest condition category (SCS). As it was stated above, in Collection 6 MODIS pixels have a minimum size of 1 sq km, while pixels with SCS information have a sinusoidal projection with a resolution of 260 sq m.

Such a difference in the geometric representation of the data creates a task of bringing them to a comparable form. In order to solve the problem, at the first stage, a coordinate grid with a cell size of 0.01 ° N by 0.01 ° E was formed, covering the entire territory of the country. Each cell with a detected fire was assigned a corresponding FRPS value for that fire. The FRPS information was taken from the previously described MCD14DL database, which was a set of pixels. Each pixel corresponds to the FRPS value of that part of the conflagration that burns in the area covered by that pixel. The developed method has implemented the correct comparison of the grid cells with those pixels. Figure 1 shows the area of the thus obtained distribution map of FRPS fires that took place in 2012 in the Russian Federation. The VEGA-PRO cartographic interface was used to compile it.

![Figure 1](image_url)

**Figure 1.** The map area covering FRPS fires distribution in 2012 in the Russian Federation using correction for all registered hot spots.

The next step in solving the task at hand was to compare maps of distributions of fires energy characteristics with maps of post-fire damages. To achieve that, the pixels with the SCS data were compared with the grid of FRPS fires distribution map; each grid cell was assigned a value of the SCS class if only pixels of one class of post-fire damages fell into that cell.

Thus, the presented methods for constructing maps of fires’ energy characteristics distribution in the Russian Federation and comparing those maps with post-fire data on forest coating damages formed a toolkit for further study of the relationship between the characteristics in question.
3. Results and Discussion
The resulting dependencies of the FRPS values hot spots and SCS classes are presented below in figure 2.

![Figure 2. Distribution of FRPS hotspots as compared to SCS classes.](image)

The distribution shows the revealed dependencies of FRPS values between classes. On the distribution basis it was found that the ‘dead’ class stands out well in the distribution of FRPS average values. For more details of the FRPS distribution for different types of territories, see the relevant article [11]. In order to proceed to the area estimates, a graph was constructed showing the dependence of the forest cover destruction probability (damage observations, classes 4 and 5) at the points of post-fire FRPS maps on their specific values. Such dependence is shown in figure 3. The FRPS scale in the graph is divided into intervals, within each of them the fraction of hotspots, classes 4 and 5, is calculated. The fifth class is considered in combination with the fourth one as it is the cover with class 4 and class 5 destruction is attributed in many studies to the dead vegetation. One can see that, starting from the FRPS value of about 80 MW / sq km and in all subsequent ranges the fraction of such points exceeds 50% which means that the destruction from fires with a high FRPS will most likely be referred to the classes of dying and dead vegetation.

The on-line assessment method of forest cover damage is based on the obtained result. Using the probability of forest destruction for FRPS values makes it possible to estimate the area of post-fire damage within each registered hotspot.
Figure 3. Fraction of hotspots referred to classes 4 and 5 in FRPS ranges.

According to the developed methodology, integral estimates of the areas with dead and dying vegetation were obtained on the territory of the entire country since 2001. Figure 4 shows a comparison of the estimates obtained with the actual area of forests destroyed by fires as per SCS maps from 2006 to 2019 [10].

Figure 4. Long-term assessment variations of the areas with dead and dying vegetation in Russian forests.

As a rough approximation, one can say that the assessment is overestimated as compared with the real data. However, in the interannual dynamics, the value of the estimated area is changed similar to the actual area. The obtained correlation between two data series is the first step in the process of validating the developed methodology. At the current stage it is necessary to eliminate the influence of
all possible errors on the ratio of the forest destruction probability and the FRPS values in order to increase the accuracy of real assessment of the area with destroyed vegetation.

4. Conclusion
The data containing information about the fires’ radiation power was used for the initial assessment of damage to the forest cover. A preliminary method was developed for comparing the FRPS-observed information with the SCS data; the method was based on using post-fire FRPS maps which made it possible to study the relationship between the intensity of fire burning and post-fire destruction.

Mutual dependences were found between FRPS hotspots and SCS classes. It was stated that vegetation remains more often drying and dead after fires with extreme radiation power values. On the basis of that result, the probability of forest death was calculated from the peak FRPS value. This ratio makes it possible to estimate the fraction of dead vegetation for each pixel, which allows in turn to estimate the area of the dead forest inside a pixel.

The results obtained were used to develop a methodology for the rapid assessment of the dying and dead forest areas as per FRPS data for individual fires [12]. The estimates of the dead and dying forest areas that were obtained using the developed methodology and applied to fires from 2006 to 2020 were correlated with data based on SCS maps providing the actual forest destruction areas and that correlation showed good comparability.

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