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Determination of the Energy Properties of Wildfires in Siberia by Remote Sensing

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Abstract—As applied to the conditions of wildfires in Siberia, remote sensing is adapted to record the radiation power from the active fire zone in the range of 3.929–3.989 μm (Terra/MODIS data). The limits of variation of the detected values of heat radiation are evaluated. Sporadic peaks that exceed the mean value of heat radiation in the fire field by a value of 2.5σ were correlated with high-intensity fires, including crown fires. The probability of remote fire detection in crown stage was no less than 65%. The quantitative dependence of the Fire Radiative Power (FRP) on the area of the active zone was determined using a subpixel analysis. The fraction of forest fires in Siberia with areas of extreme heat radiation is shown to be 5.5 ± 1.2% of the total wildfires. The total area of high-intensity wildfires including crown fires is at least 8.5% of the average annual wildfire area and reaches values of 15–25% during extreme fire seasons.

Keywords: vegetation fire, active fire zone, fire radiative power, crown fire, sub-pixel analysis

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INTRODUCTION

The Siberian territory accounts for up to 70–90% of the annual number of wildfires in Russia (Forkel et al., 2012; Shvidenko and Shchepashchenko, 2013; de Groot et al., 2013). Approximately 30% of the total number of recorded fires are accompanied by subsequent decay or replacement of stands (Krylov et al., 2014); up to 1.5–3 million hectares of forest perish annually as a result of fires, according to some estimates (Bartalev et al., 2015).

Climate change and positive trends in forest burning lead to development of effective methods of operational registration of the main properties of fires. Such data are necessary both for the purpose of daily monitoring and forecasting post-fire processes. One of the important characteristics of a fire is its intensity. Differential recording of the energy properties of fires will form an information-based and methodological basis for predicting the degree of fire impact on vegetation, as well as for refined estimates of fire emissions on regional and global scales.

The realization of these tasks at the scale of Siberia (especially for the entire territory of Russia's forests) is impossible without using remote satellite data. The experience of their application in the monitoring of fires and the post-fire condition of forests has been discussed in many studies (Ponomarev and Buryak, 2007; Krylov et al., 2014; Bartalev et al., 2015). Increasing the accuracy of remote assessments has been shown to require a conjugate analysis of satellite information and ground survey data (Buryak et al., 2011). However, this approach is implemented only at model sites or in local areas due to the need for a series of satellite experiments.

When classifying satellite imagery data, in particular, using well-known approaches based on information processing in the "vegetation" channels of radiometers (channels 1 and 2 of Terra/Aqua/MODIS (Moderate Resolution Imaging Spectroradiometer), where the wavelength ranges are, respectively, $\lambda_1 = 0.620–0.670$ and $\lambda_2 = 0.841–0.876$ μm, it is often difficult to interpret the result due to lack of reliable information about the classes of damage since the signs of the areas covered by a fire change with time or even are lost.

An alternative method for predicting post-fire changes is based on satellite imagery in the middle infrared (IR) range (channel 21 of the MODIS radiometer with an operating range of $\lambda = 3.929–3.989$ μm). The magnitude of the signal detected in a given range of the electromagnetic spectrum is related to the power of heat release from the active zone of a fire. This property is known as the "radiation power of a fire" or "radiant power" or Fire Radiative Power (FRP) in the literature (Kaufman et al., 1998). A remotely determined indicator of the radiant power was tested in areas of active combustion, including model and full-scale fires. As an example, a high correlation between the detected heat radiation with the quantitative properties of biomass burning in meadow vegetation fires was found (Boschetti and Roy, 2009, Kumar et al., 2011). Data on the ratio of the power of heat radiation and the combustion area were given elsewhere (Mottram et al., 2005). As well, the first remote assessments of integral heat radiation from the fire fields in various forest stands in Siberia were obtained (Ponomarev, 2014; Shvetsov and Ponomarev, 2015).

The heat-radiation power associated with the amount of burning biomass can be used as a criterion for detecting the degree of damage to forest vegetation. The proposed approach is particularly effective for detecting fires of extreme intensity, as well as for cases of crown fires.

This study is aimed to improve the methods of remote monitoring with regard to registration of fires and fires of extreme intensity, as well as a quantitative assessment of their fraction in the statistics of wildfire risks in Siberia.

On the practical side, the results of the study will complement the information content of operational remote database on fires. In particular, the method of remote evaluation of the energy properties of the active burning zone has been adapted with respect to the fire conditions in Siberian forests.

The following aspects of the problem are considered in this paper: (i) the dependence of the recorded power of heat radiation on the subpixel area of an active zone, (ii) evaluation of the effectiveness of remote methods of registering extreme-intensity fires under the fire conditions of Siberia, and (iii) the quantitative properties of the fraction of fires with extremely high energy properties in the long-term statistics of wildfire in Siberia.

MATERIAL AND METHODS

As initial information on the location and dates of fires in Siberia (50°–70° N, 80°–130° E) we used a vector polygonal layer based on a series of consecutive thermal anomaly registrations with MODIS of Terra and Aqua satellites. The methods of completing a fire database of the V.N. Sukachev Institute of Forest (IF SB RAS) and its contents were described in more detail in a series of our previous studies (Ponomarev and Shvetsov, 2013, 2015). Data for the period of 2006–2015 were used in this study.

The power of the heat radiation was calculated based on measurements of the radio brightness temperature in channel 21 of the MODIS radiometer of the Terra and Aqua satellites. The MOD14 and MYD14 products were used, respectively (Giglio, 2013; NASA LAADS Web, 2016). The initial data were transformed by the geographic information system (GIS) into point vector coverage. The coordinates of each point were tied to the center of the corresponding active (“fire”) pixel, while the value of the heat radiation and the date and time of the survey were also shown. On average, up to 50–100 measurements of the heat radiation power were obtained for each fire polygon using the Institute of Forest SB RAS database (Fig. 1b).

The spatial resolution of the MODIS data is 1000 m. However, the size of the ground-based pixel projection can be significantly overestimated at large scanning angles, reaching up to 10 km^2 at the edges of the survey strip. It is estimated that up to 12% of all captured pixels can contain such an overestimate. Uncertainty in the area of the recorded pixel leads to an increase in the power of the heat radiation since the radiation power value is linearly related to the pixel area in the MOD14 product, ver. 5 (Kaufman et al., 1998; Justice et al., 2002):

$$FRP_{px} = 4.34 \times 10^{-19} \left(T_{tg}^{8} - T_{bg}^{8}\right) S_{px},$$

where T_{tg}^{8} and T_{bg}^{8} are, respectively, the brightness of the “fire” pixel (target) and the background in the range of 3.929–3.989 μm, and S_{px} is the area of the pixel, m^2.

To avoid overestimating the values of heat radiation, the normalization is performed to the actual area of the pixel calculated by the formulas given elsewhere (Ichoku and Kaufman, 2005). Thus, the original data were transformed to the radiant power from the unit area of the active pixel. This took the area of the surface projection of the pixel into account and the area of the high-temperature zone (S_{tg}) obtained based on a subpixel analysis. A bispectral method was used (Dozier, 1981) to evaluate the properties of small fires (a fire size smaller than the instantaneous field of view of the scanning equipment), such as the area and the radio brightness of the active fire zone. In the case of a small thermal anomaly, the instantaneous field of view of the radiometer covers both the zone of active combustion with a temperature of T_{tg}, which occupies the fraction p of the pixel ($0 \le p \le 1$), and the background with the temperature T_{bg}, which accounts for the rest of the pixel ($1 - p$). The recorded thermal radiation in the absence of the influence of the atmosphere is written in the form of the following system:

$$\begin{cases} L_4(T) = p \times L_4\left(T_{tg}\right) + (1-p) \times L_4\left(T_{tg}\right) \\ L_{11}(T) = p \times L_{11}\left(T_{tg}\right) + (1-p) \times L_{11}\left(T_{tg}\right) \end{cases},$$

where $L_4(T)$ and $L_{11}(T)$ are the thermal radiation registered in the ranges of ~ 4 and ~ 11 μm, respectively, by the Terra/MODIS radiometer and T_{tg} and T_{bg} are the values of the target temperature (active burning zone) and the background, respectively.

To solve the inverse problem of determining the temperature of (T_{tg}) and the fraction of the active zone (p) in a pixel, numerical methods for solving a

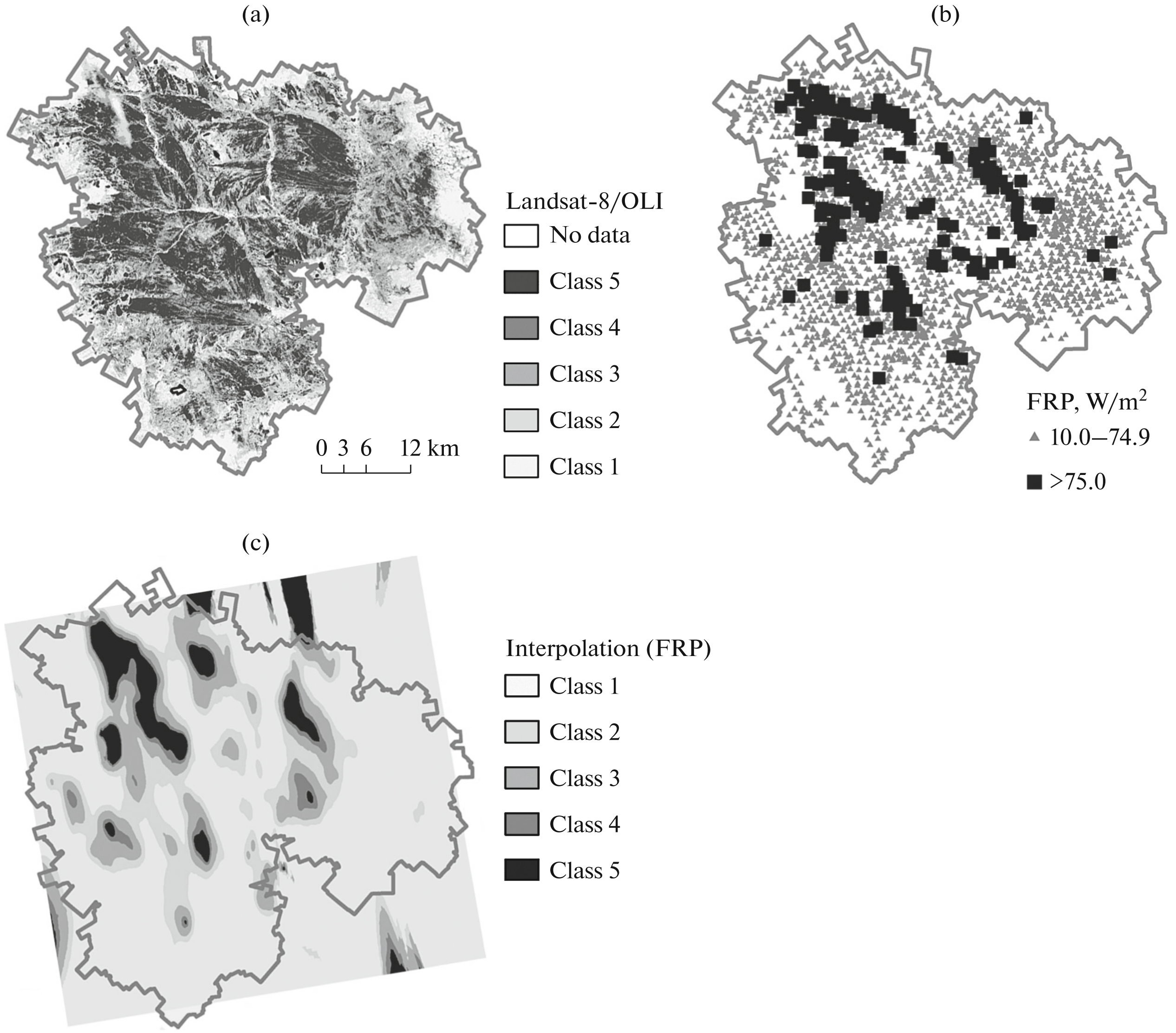

Fig. 1. An example of a fire polygon: (a) Classification of the degree of impairment according to Landsat-8/OLI, (b) Terra/MODIS heat radiation power, and (c) kriging interpolation of FRP values.

system of nonlinear equations are used at a known background temperature of T_{bg} (Dozier, 1981), which is determined using the values of neighboring pixels that are not related to thermal anomalies. Further, the absolute value of the area of the high-temperature zone was determined as follows:

$$S_{tg} = p \times S_{px},$$

where S_{px} is the surface area of the ground projection of the pixel.

The obtained radiant power values were combined (Figs. 1a and 1b) with a polygonal GIS layer of fires from the database of the IF SB RAS based on the spatial (fire field boundary) and temporal criterion of the coincidence (the start and end dates of the fire). A sample for fire fields with an area of more than 2000 ha was considered, which together cover more than 90% of all areas exposed to fire over the year. Fires with an area of less than 2000 ha corresponded to not more than 2% of the active pixels characterized by extreme values of the heat radiation power.

The heat radiation power, standard deviation, and confidence interval averaged over all active pixels were calculated for each fire polygon. The condition for assigning an active pixel to the category of extreme energy fires was exceeding the threshold value:

$$\mathrm{FRP}_{\mathrm{extr}} > \mathrm{FRP}_{\mathrm{mean}} + 2.5 \times \sigma_{\mathrm{FRP}},$$

where $\mathrm{FRP}_{\mathrm{mean}}$ and σ_{FRP} are the mean value of the radiation power and the standard deviation from the average, respectively, for all the pixels within the boundaries of a given fire polygon.

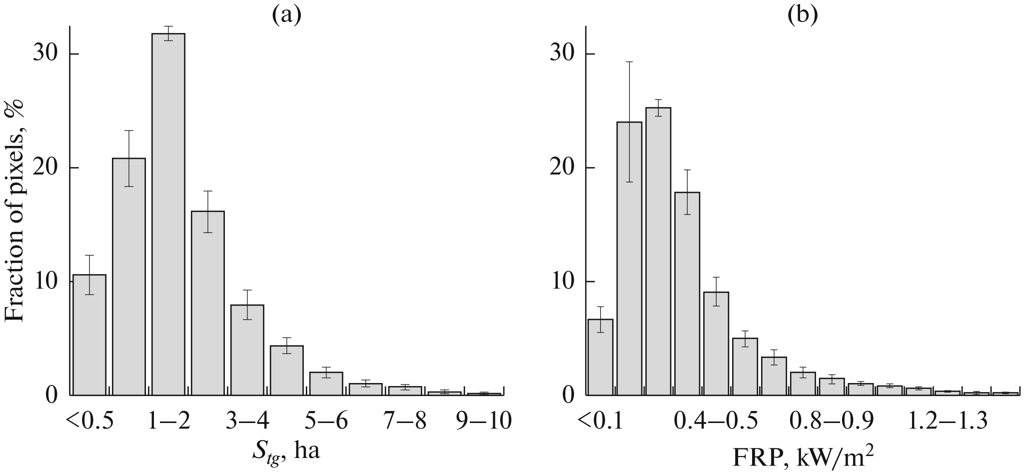

Fig. 2. The distribution of pixels over the intervals of values: (a) area of the active zone of fire based on a subpixel analysis and (b) heat radiation power in a pixel. Confidence interval limits are indicated at $p < 0.05$.

A conjugated analysis of the results of the classification of post-fire areas was performed by GIS tools using the survey data of the Landsat 8 OLI (Operational Land Imager) satellite and kriging interpolation (Materon, 1968) of FRP values based on the Terra/MODIS survey data. The degree of damage qualitatively represented by five classes was compared with the maximum power of heat radiation (Fig. 1). In addition, result validation was carried out using data on crown fires in the Krasnoyarsk region obtained by the Service of ground and aircraft protection of forests (more than 70 points with coordinate and time reference). The spatio-temporal coincidences of the active pixels with the extreme FRP values with the coordinates of the crown fires were analyzed. Taking the resolution of the initial satellite data into account, the permissible spatial discrepancy is accepted equal to 1000 m.

In addition, GIS statistics of Siberian fires with extreme FRP values were obtained for 2006–2015.

RESULTS AND DISCUSSION

The vegetation damage classes allocated in the Landsat/OLI images according to the values of the vegetation index (NDVI is Normalized Difference Vegetation Index) after a fire are consistent with the distribution of the heat radiant power of the active zones. Interpolation of a series of measurements inside the polygon allowed the identification of areas with extremely high FRP values, which were correlated with the class corresponding to the highest level of vegetation damage according to the Landsat data. The points with values of the radiant power that satisfy the proposed criterion of $\mathrm{FPR}_{\mathrm{extr}}$ are shown in Fig. 1b. The relative error in determining the area of extreme heat radiation in comparison with the degree of vegetation damage according to Landsat (class 5) varied at the level of 12–25%.

Obviously, the discrepancy is determined by the different resolutions of the used data (1000 m vs. 30 m in the Landsat/OLI data).

However, the proposed approach based on Terra/MODIS data is characterized by higher operability and the possibility of multiple iterative refinements during the detection of thermally active zones, which is required for present satellite monitoring systems.

The data of the entire sample of pixels are presented on the distribution histograms over the intervals of the detected values (Fig. 2). The detected areas of the active zone of the fire (Fig. 2a), as well as the values of the heat radiation power (Fig. 2b) are quasinormally distributed. The subpixel analysis recorded the largest frequency of the areas of thermal anomalies in the range of 1–2 ha (up to 31.8 ± 0.6% of all the studied pixels). Up to 49.4 ± 0.7% of the sample of pixels with studied thermal anomalies were characterized by heat radiation in the range of 200–300 W/m^2.

The dependence of the heat radiation power on the subpixel area of the active zone has a wide range of values (Fig. 3) and is determined by the variation in the combustion rate under various external conditions: the prevailing type, state, and degree of readiness of combustible plant materials. The distribution of the initial data in the space of the $\mathrm{FRP}_{\mathrm{mean}}$ and S_{tg} attributes depending on the type of the prevailing stand does not qualitatively change (Figs. 3a–3d). The presence of a group of pixels should be noted with FRP values of ~1650 W/m^2 recorded for high-intensity fires in coniferous forests (Figs. 3b and 3c) and associated with the saturation of the middle IR channel of the MODIS radiometer (3.929–3.989 μm) upon detecting active pixels with extremely high heat radiation.

Averaging over the areas of the active zone and over the power of the heat radiation makes it possible to quantify the relationship between the studied parame-

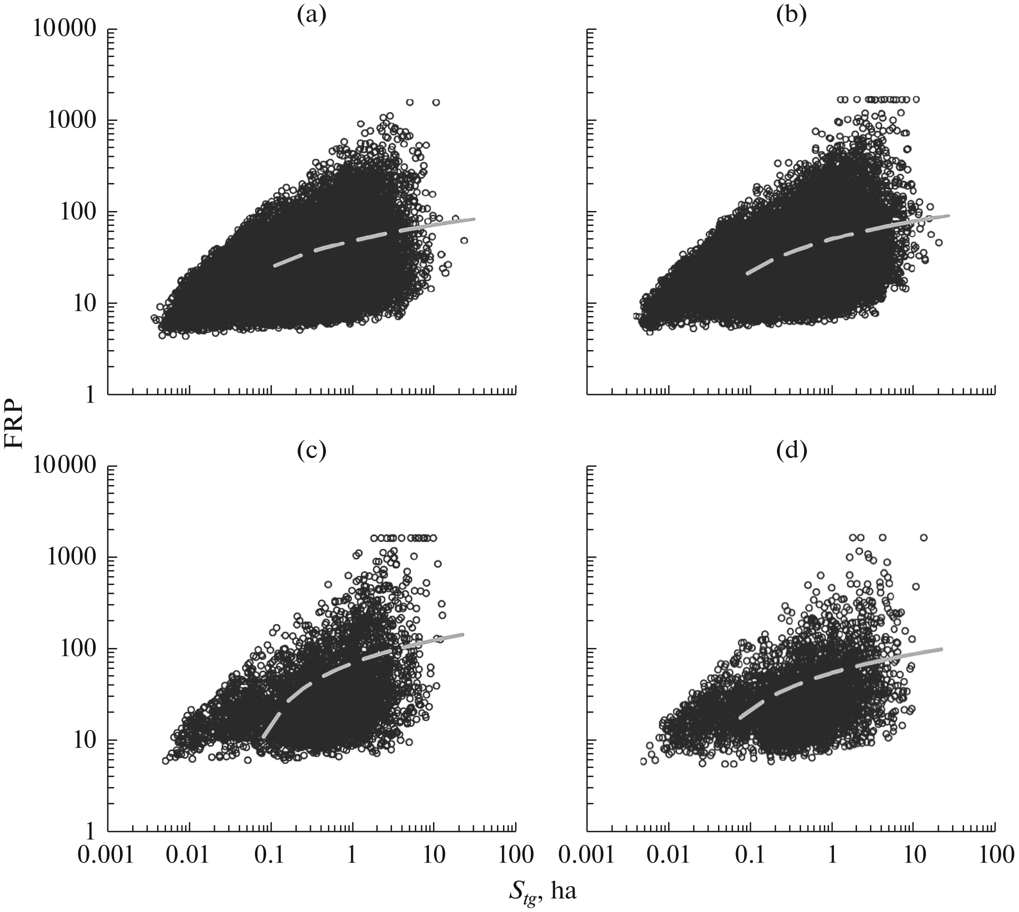

Fig. 3. The initial data in the logarithmic space of the $\mathrm{FRP}_{\mathrm{mean}}$ and S_{tg} attributes: (a) non-forest fires, (b) fires in forests with a predominance of light coniferous trees, (c) fires in dark coniferous forests, and (d) fires in deciduous forests.

ters. In the first approximation, the regression equation has a linear form (Fig. 4a) with the reliability of the approximation at the level of $R^2 = 0.9$. Sections of the curve at the smallest and the large areas of the active zone of fire in a pixel are of interest. For areas of less than 1200 m^2, a section of the curve is distinguished with a logarithmic type of dependence (Fig. 4b). Taking the variance of the recorded values into account (including the maxima in the saturation region), the distribution is close to exponential at areas greater than 50×10^3 m^2.

In this paper, the heat radiation power was calculated from the unit area of the registered pixel while in the literature data, as a rule, the power is given from the unit of the area of the fire front. The experimentally obtained radiant power values depending on the external conditions and the type of forest fuel are 28–750 kW/m^2 (Konev 1977, Valendik and Kosov, 2008) while the values reach up to 5000–60000 kW/m^2 for high-intensity fires (Stocks and Hartley, 1995). The values calculated for a pixel of the Terra/MODIS image (1000 × 1000 m) will be lower by 3–4 orders of magnitude, on average. More than 90% of all processed active pixels had FRP values in the range of 10–300 W/m^2 (Shvetsov and Ponomarev, 2015) with allowance for the actual fraction of active burning (p) within the pixel. The criterion for registering the pixels of the extreme heat radiation used in this work, $\mathrm{FPR}_{\mathrm{extr}}$, was not lower than 75 W/m^2. It should be also noted that it was shown earlier that the integral heat radiation from the entire fire polygon can vary in a wide range of 1200—75 000 MW (Ponomarev, 2014). Such high values of heat radiation are mostly determined by “catastrophically” large areas of wildfires (more than 50 000 hectares), which are not rare in Siberia.

In the final part of the study, this approach was used to process data on fires for the period of 2006–2015. For the first time, it was instrumentally recorded that the fraction of high-intensity fires in Siberia varies annually at a level of 5.5 ± 1.2%. The total area of high-energy fires, including crown fires, was at least 8.5% of the average annual area of fires and reached 15–25% of the total area of fires in some years (e.g., 2009, 2010, and the extreme season of 2012). Recorded extreme values of FRP are mostly associated with the phase of the maximum combustion intensity. This is

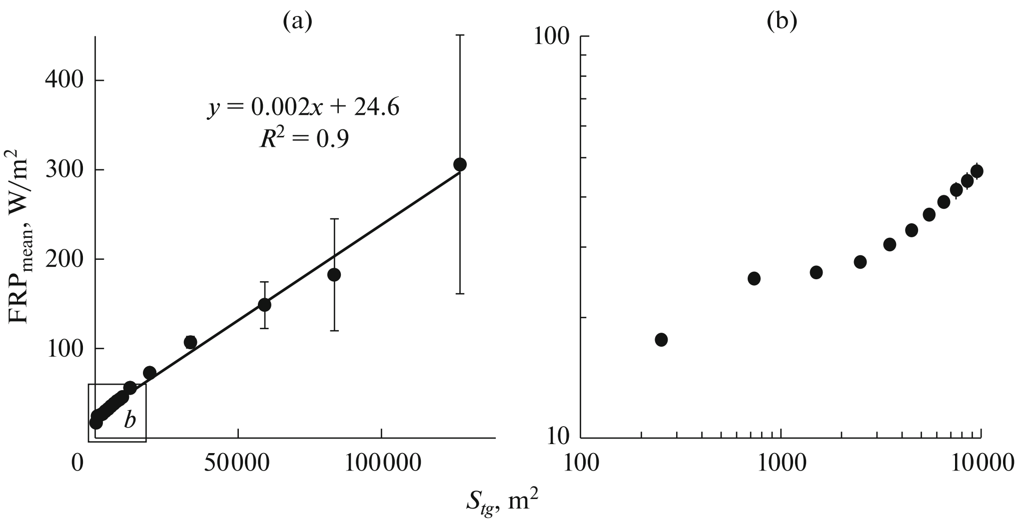

Fig. 4. The averaged values of the registered FRP from the area of the active zone within the pixel boundaries of the image: (a) a complete data set and (b) the dependence for small areas of the active zone.

confirmed by the results of conjugate analysis with information about the crown fires. Approximately 65% of the wildfires recorded by ground observations were accompanied by extremely high FRP that exceeded the average values for the fire polygon by more than 2 times.

The possibilities for registering fires (including crown fires) and for reacting to them are objectively determined by technical parameters of the equipment, existing data-processing technologies, and the level of interaction management. In the operational work, there is, in fact, a need for updating the instrumental and technical equipment of the monitoring system, including involvement of Russian satellite systems and increasing the requirements for the accuracy of estimates, the data updating, and the reliability of forecasting. The ecology issues of forest fires also should be mentioned. An analysis of the energy properties of fires is fundamentally important for assessing the fire impact on vegetation, monitoring emissions, and predicting the post-fire state of forests. In this sense, taking the properties of individual sites within the boundaries of the fire polygon as characterized by unique energy characteristics into account is critically important, while remote sensing remains the only source of instrumental data for qualitative and quantitative assessments of wildfires and for predicting post-fire effects on the Siberian scale.

CONCLUSIONS

The remote sensing of the heat radiation power from active fire zones in the range of 3.929–3.989 μm (Terra/MODIS data) was first tested and adapted for forest fire conditions in Siberia.

The heat radiation power depending on the subpixel area of the active combustion zone shows a spread in a wide range while the dependence is reliably approximated ($R^2 = 0.9$) by a linear function in the first approximation. In practice, this means the ability to instrumentally estimate the area of the active zone of the crown fire phase when monitoring a fire remotely. This is directly related to the problem of monitoring and predicting the degree of vegetation damage after a fire.

The heat radiation from high-intensity fires and crown fires is found to exceed the 2.5σ threshold of the average value for the fire polygon ($p < 0.05$). The probability of correct classification of a crown fire was at least 65% according to remote-sensing data.

In Siberia, the fraction of high-intensity fires varies at a level of 5.5 ± 1.2% per year. According to the processed remote sensing data over a 10-year period, the total area of high-energy fires, including crown fires, was at least 8.5% of the average annual area of fires and reached 15–25% of the total area of fires in some years.

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