

INTRODUCTION

Russia accounts for about half of the world's forests, most of which are in Siberia. Numerous forest fires, mostly human-caused, and extensive forest harvesting, including illegal logging, have resulted in considerable ecological damage and economic loss. At present, forest inventory agencies assess the effects of fire based on the known forest area burned. Due to potential cost and difficulty of access types and severity of fire effects are normally not assessed. The lack of reliable estimates of ecological and economic impacts of forest fires prevents development of effective approaches for forest management and forest fire protection. Remote sensing and GIS-based technologies provide for the development of fundamental new methods to assess and monitor forest condition and wildfire behavior and effects. Wildfire and insect and disease outbreaks are the main natural factors responsible for partial or complete mortality of forest stands in Siberia. Negative human influences include forest harvesting, mining, industrial pollution, and human-caused fires. Estimating the scale, rate, and severity of disturbance is of key importance for appraising the resulting ecological and economic damage.

In this study, we developed a GIS- and satellite-based methodology to appraise forest damage by taking advantage of unique spectral signature of the underlying forest types. Our focus was on an area of intensive forest harvest in the Angara river basin, which includes the southern and central taiga zones. We have assessed the type, extent, and severity of disturbances in vegetation cover and mapped the current condition of disturbed forest sites. The Fire Effects in the Boreal Eurasian Region (FIRE BEAR) Project was able to monitor a number of experimental fires, along with some wildfires, to better understand and predict fireline intensities, spread rates, and fire severities in the Krasnoyarsk Region during 2000-2007. A component of this study was to link these ground measurements with air-borne and satellite observations of active wildfires and older fire scars to better estimate fire severity remotely. This has provided us with a means to estimate fire type (i.e., surface or crown fire), fireline intensity, and fire severity. The results of our ground observations on experimental and wildfires were linked with intermediate-resolution satellite (Landsat Enhanced Thematic Mapper) data in order to estimate fire severity and carbon emissions. Results are being applied to Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) imagery, MERIS, Landsat-ETM, and SPOT4, using low, middle and high spatial resolution, to understand their remote-sensing capability for mapping fireline intensity and fire severity.

1. METHODS

To achieve the study objective, we used ERDAS IMAGINE Geographic Information System (GIS) meant for processing raster images provided by different satellites. Multi-band Landsat images and active fire (hot spot) information from NOAA satellite thermal channels were used. Each underlying surface element is known to have its specific spectral response, or spectrum. These spectra help recognize vegetation types, disturbed sites, population units, and agricultural areas. The effectiveness of Landsat ETM+ imagery for estimating forest disturbance levels was assessed by analyzing image pixel brightness trends depending on forest type and level of disturbance for undisturbed and disturbed forest sites, respectively. Fire-caused disturbance level characterized mainly by stand mortality percentage of the total pre-fire standing crop and post-logging forest regeneration were assessed using Normalized Difference Vegetation Index.

1.1. Stand disturbance class determination

The study used Landsat ETM+ scenes P13R01819 (dated Sept,7,2006), P13R018 (Aug.13,2006), and P13R7019 (Aug.12,2002), P and R being column and line numbers of a satellite pass scheme, respectively. NDVI values for each image and were based upon to determine tree condition classes in disturbed sites. NDVI proved to be highly helpful in quantifying biomass.

Fig. 1. Example of Fire-Caused Boreal Forest Disturbances in Krasnoyarsk region. Logging and burned sites representative of different tree condition classes were identified in the Landsat ETM+ images based on the developed NDVI values and divided into the following four tree condition classes based on percentage tree mortality: - Disturbance class I – 80-100% tree mortality, where the NDVI is ~ -0.3; - Disturbance class II – 50-80% tree mortality, where the NDVI is ~ 0.1; - Disturbance class III – 20-50% tree mortality, where the NDVI is ~ 0.14; and - Disturbance class IV – up to 20% tree mortality, where the NDVI is ~ 0.2.

Logging sites were divided into the following four regeneration classes by age: 1- 0-1 years old, where the NDVI is ~ -0.3; 2- 2-5 years old, where the NDVI is ~ -0.2; 3- 6-10 years old, where the NDVI is ~ -0.3; and 4- 11-16 years old, where the NDVI is ~ -0.4.

Fig. 2. The spectral curves of the post-fire vegetation condition classes.

Fig. 3. The spectral curves of the post-logging vegetation condition classes.

Fig. 4. The spectral curves obtained for undisturbed vegetation types.

Fig. 5a. Classification of different levels of tree mortality.

Fig. 5b. Spine smoothing of polygons.

Fig. 5c. Counts of the class mortality on the original image.

Fig. 2. The spectral curves of the post-fire vegetation condition classes. Fig. 3. The spectral curves of the post-logging vegetation condition classes. Fig. 4. The spectral curves obtained for undisturbed vegetation types. Fig. 5a. Classification of different levels of tree mortality. Fig. 5b. Spine smoothing of polygons. Fig. 5c. Counts of the class mortality on the original image.

1.2. Estimation of disturbance levels within burned sites

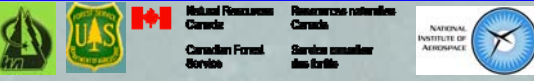
We used the 2006 Landsat ETM+ images to delineate the 2006 burned site contours, calculate NDVI values, and do automatic classification based on a training sample in order to identify vegetation disturbance classes within each burned site. The 2002 Landsat ETM+ and 1993 Landsat TM scenes were used to determine the difference between pre- and post-fire NDVI values. Other materials used were fragments of Kodnik FMA vegetation map, FMA and forest district boundary vector layer, a vector layer of the 2006 spaceborne-detected hot spots, and 1:200,000 vector topographic maps. Thirty sites burned in 2006 and totaling 3133sq km, were identified in the 2006 Landsat ETM+ scenes P13R01819 and P13R018. The site boundaries were obtained by ERDAS IMAGINE GIS-based analysis of these scenes using a method of region growing (ERDAS IMAGINE Field Guide). The scenes were received in 2006 after the fire season. The presence of active fires was confirmed by hot spots identified by NOAA-AVHRR thermal channels. As was clear from the data provided by the satellite information receiving station installed in Krasnoyarsk, the 2006 fire season lasted from June 5 to August 16 in the area of interest. The burned sites under study resulted from fires of varying intensity. In an attempt to estimate post-fire disturbance classes these burned sites were divided into two categories based on pre-fire condition: (1) single-disturbance sites that contained the overstory layer and (2) repeatedly disturbed sites (burned of harvested) that contained either no, or sparse (open) overstory. Disturbance classes were derived from post-fire NDVI values for sites of the first category. NDVI values calculated for one of these sites are shown in Fig. 5 as a range of grey, with a darker tone corresponding to lower index values. This figure clearly shows non-uniformity of NDVI values within the burned site. Five disturbance classes were identified for burned sites, with higher class numbers corresponding to lower disturbance severity. The entire range of NDVI values found for burned sites was divided into five groups at an equal (similar) interval. The following NDVI values appeared to correspond to the disturbance classes obtained:

Class I, where the NDVI is ~0.1; Class II, where the NDVI is 0.13; Class III, where the NDVI is 0.16; Class IV, where the NDVI is 0.29; and Class V, where the NDVI is 0.42.

Disturbance level depends largely on fire shape and intensity. A steadily spreading fire, for example, burns deep into the forest and heavy disturbance occurs due to long fire residence time resulting in that tree roots and phloem are damaged by fire. Fire type, shape, and intensity (severity) are, in turn, determined by forest stand characteristics, topography, soil moisture content, and probably by time during the day and relative air humidity. A part of the forest stands under study, mainly middle-aged conifer stands dominated by Scots pine (*Pinus sylvestris*) and mature dark-needled stands with dense young conifer regeneration, experienced crown fire that resulted in 100% tree mortality (disturbance class I), as was clear from remote sensing data. Surface fires of varying shape and mixed severity appeared to be more common. Tree mortality was estimated to exceed 70-90% (disturbance classes I and II) after a high-severity steadily spreading surface fire. Fires of this type, shape, and severity are characteristic of moderately stocked stands on wet soils. Most of the trees killed by fire fell down by autumn 2007, only single large trees situated on elevations survived this fire. Tree mortality did not exceed 40% (disturbance class IV) in mixed mature conifer stands after a fire of low-to-moderate severity. Such fires are common in mature and overmature well-stocked stands with feather-moss-dominated surface vegetation. However, tree mortality induced by this fire might increase in time, because the highest surface fuel consumption occurred in the close vicinity of trees and each tree appeared to have roots damaged by fire. The post-fire tree mortality was found to range 40-60% (disturbance class III) in stands of lower stocking densities. Surface fuel consumption by fire generally exhibited a mosaic pattern in well-stocked middle-aged stands, which might be attributed to high moisture content of these fuels represented by a deep feather moss layer. While fire consumed most of the fuel around tree stems, it burned only the upper surface fuel layer in the major part of the site area and some places even remained unburned. Tree mortality was calculated not to exceed 20% (disturbance class V) on these sites by fall 2007. Many of dense mixed deciduous/conifer young stands situated in the middle of burned areas were observed to be left unburned, which case also corresponds to disturbance class V. Disturbance class identification was not attempted for sites of the second category (i.e., for repeatedly disturbed sites), since complete or almost complete absence of forest made this identification pointless in terms of forest use. Our main objective was just to separate such sites with the help of Landsat images obtained before 2006. To recognize the above disturbance classes, a training sample was made and the 2006 Landsat ETM+ images were classified using a maximum likelihood method. The raster classes obtained were converted into a vector form representing them as polygons. These polygons that did not matter much in terms of the general underlying surface picture merged with bigger polygons. The rectangular polygonal disturbance class boundaries characteristic of pixels making up raster images were smoothed to be close to those of natural objects. The vector layer of boundaries of different disturbance classes was superposed on raster images provided by Landsat ETM+ visible bands. Reflective surface albedo, burned surface, in our case, was assumed to vary among disturbance classes. Based on this assumption, areas under different disturbance classes would visually differ in color. The disturbance class boundaries obtained using automatic classification were found to coincide with those of the classes visually differing in color in an RGB composite.

Fig. 2. The spectral curves of the post-fire vegetation condition classes. Fig. 3. The spectral curves of the post-logging vegetation condition classes. Fig. 4. The spectral curves obtained for undisturbed vegetation types. Fig. 5a. Classification of different levels of tree mortality. Fig. 5b. Spine smoothing of polygons. Fig. 5c. Counts of the class mortality on the original image.

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2. FIRE SEVERITY

Fire severity definition and measurement units
Fundamentally, fire severity definition, should be based on an understanding of heat mass transfer that occurs during forest fires, as well as the impact of fire on vegetation. This requires that flame and smoldering zone heat fluxes be related to the postburn plant state (e.g., condition, health, etc.). The lethal (stress or mortality) temperature for plant tissue is 50°C. To understand this impact, it is necessary to estimate flame and smoldering zone heat fluxes received by these plant tissues and to calculate their temperatures. Where the temperature is higher than 56°C, plant survival will depend on the percentages of the plant subjected to the stress temperatures. Calculating lethal temperatures should be based on fire temperature fields and residence times. These can be obtained using fire behavior models or field experimental data. Fire severity quantification needs to be improved, since this is an important positive stand replacement criterion.

2.1. Seasonal Normalized Difference Vegetation Index (NDVI) variability and fire severity.

Ground vegetation tree crowns have specific dynamic spectral reflectances that can help in understanding the type of fire and its impacts. These signatures can help readily identify:
• Percentage of stand canopy completely destroyed by crown fire (Fig. 6a, black, low NDVI, 100% tree mortality)
• Percentage of remaining canopy, which is, however, brown due to crown scorch resulting from lethal temperatures (Fig. 6b; brown, mid-range NDVI, high tree mortality)
• Stand canopy remains green indicating it was a surface fire that had not harmed mature trees. (Fig. 6c; green, high NDVI, little or no tree mortality)

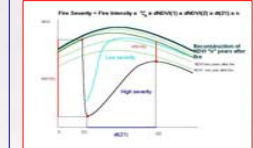


Figure 7. Seasonal NDVI dynamics for different fireline intensities.

2.2. Ground validation of indexes for different fire scars and cutting area

Fire scars in the Angara Region of central Siberia (northeast of Lake Baykal, Fig. 8) were studied for which ENVISAT-MERIS and Landsat-ETM images and ground validation data were available for the 2003-2004 and 1996-2004 periods, respectively. Ground validation was conducted on thirty sample plots established on burned sites differing in age, stand structure and composition contained in the images. Images were obtained for various sampling locations to indicate tree mortality (%) at the time of observation (2003, 2004, and 2005).

Satellite images taken during the growing season (June - August) were selected for analysis. Two MERIS scenes were chosen (18 June 2003 and 27 June 2004), which appeared to have been taken closest to our fieldwork periods. Images were selected based on minimum cloud and smoke cover. Values of $NDVI_{REP}$, $INDEX 57$, and $INDEX 54$ were calculated for each image pixel using Equations 1, 2, and 3, respectively, with $NDVI$ values being calculated from MERIS Channel 8 (681.25 nm) and 13 (865.00 nm) data.

Ground sample plots were established so that they contained an average of 9 MERIS pixels (81 ha). The test site shape and size were determined visually based on the homogeneity of the site in the MERIS image and in the superimposed composite high-resolution PAN Landsat-ETM images (15-m pixel size). In some cases where the individual sample fire areas were less than one MERIS pixel, smaller sample areas were aggregated into a single test site to create a sample area of 9 MERIS pixels. In all cases, average tree mortality was determined. Average spectral reflectance (Fig. 9), as well as $NDVI_{REP}$, and $INDEX 57$ were determined for each test site. Prefire imagery information was obtained from MERIS images taken before each fire. A total of 19 sites were sampled on burned areas and 10 sites were used as controls to investigate the relationship between stand mortality and vegetation indexes related to burn severity.

$$NDVI = \frac{R_{0.82} - R_{0.66}}{R_{0.82} + R_{0.66}} \quad \text{From Landsat-ETM imagery} \quad \text{INDEX 57} = \frac{R_{1.65} - R_{2.22}}{R_{1.65} + R_{2.22}} \quad (1)$$

$$INDEX 47 = \frac{R_{0.82} - R_{2.22}}{R_{0.82} + R_{2.22}} \quad \text{INDEX 54} = \frac{R_{1.65} - R_{0.82}}{R_{1.65} + R_{0.82}} \quad (16)$$

$$REP(MERIS) = 708.75 + 45 \left(\frac{R(MERIS) - R_{burn0}}{R_{burn10} - R_{burn0}} \right) = 708.75 + 45 \left(\frac{R(MERIS) - R_{burn0}}{R_{burn10} - R_{burn0}} \right) \quad (2)$$

$$MTCI = \frac{R_{burn0} - R_{burn10}}{R_{burn0} - R_{burn25}} = \frac{R_{0.82} - R_{0.78}}{R_{0.82} - R_{0.78}} \quad (3)$$

where $R(MERIS) = \frac{(R_{burn0} + R_{burn10})}{2} = \frac{(R_{0.82} + R_{0.78})}{2}$

Results of the ground validation of indexes for the different fire scars and cutting areas are presented in Tables 1 and 2, and Figures 8 and 9. Note the linear relationship which statistically confirmed between tree mortality and MTCI and NDVI indexes. This allows to estimate the level of forest disturbance using only satellite images with middle- or high-spatial resolution.

CONCLUSION

(1) A new method of monitoring and documenting fire behaviour, including fire intensity, fire energy release, fuel consumption, rate of spread, probability of crowning fires, fire severity, using multi-spectral aerial and satellites imagery and GIS technology is discussed. Fire intensity can be estimated using infrared thermal imagery only. Fire severity in terms of mortality depends on fire intensity, residence time, and the physiological effects on the cambium layer, foliage and roots. Fire severity can be estimated from NDVI and other Chlorophyll Indexes using linear relationships between tree mortality and indexes. The validation data obtained on experimental and wildfires are being analyzed and compared with intermediate-resolution satellite data (Landsat-ETM) to help estimate fire severity, emissions, and carbon balance. In addition, it is being used to monitor immediate ecosystem fire effects (e.g., tree mortality) and long-term positive vegetation recovery. This data is also being used to validate AVHRR, MODIS, and MERIS estimates of burn area. Accurate fireline intensity estimation appeared to be virtually impossible without the use of infrared imagery. Fire severity was found to depend on fireline intensity, residence time, and their effects on tree tissues. NDVI and MTCI were proven to be a useful remote-sensing tool for estimating fire severity based on tree mortality. Further development and testing of these relationships will enable accurate, broad-scale mapping of fire intensity, severity, along with the extent of wildland fires in Central Siberia.

(2) Presently, there are no viable alternatives to this approach. High spatial resolution infrared images obtainable from satellites are not commercially available at present. Even if they were, the problem still exists that these satellites are usually not overhead or, if present, cannot remain overhead for the entire period of active burning. In addition, because the satellites are not usually directly overhead in the boreal region, only oblique images are possible which make reliable analysis impossible. A new satellite system must be developed for early fire detection and fireline mapping and energy diagnostic at northern latitude; the satellite instruments must provide high spatial resolution in infrared bands (better than 200 m) and short revisit time (less than 2 hours). Nearest analogue of such satellite was German satellite BIRD and world fire specialists and scientific community must support German Space Agency in the developing of the International Fire Monitoring Space System.

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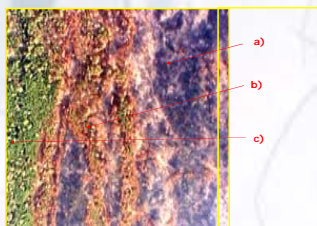


Figure 6. Images of fire effects showing impacts of different fireline intensities on tree mortality: (a) high-intensity crown fire resulting in 100% tree mortality, (b) high-intensity surface fire resulting in high tree mortality, and (c) low-intensity surface fire resulting in little tree mortality.

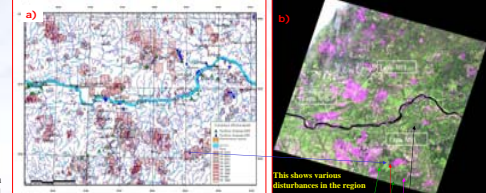


Figure 8. Test plots distribution for fire severity ground validation in the Angara Region showing: a) disturbance distribution map, and b) Landsat-ETM image (Channel 4, 5, and 7) of the same area.

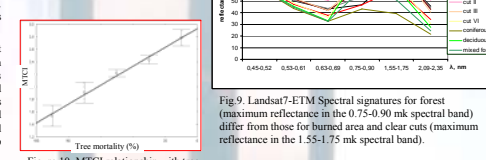


Figure 9. Landsat-ETM Spectral signatures for forest (maximum reflectance in the 0.75-0.90 µm spectral band) differ from those for burned area and clear cuts (maximum reflectance in the 1.55-1.75 µm spectral band).

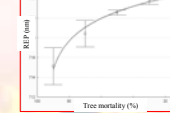


Figure 10. MTCI relationship with tree mortality.

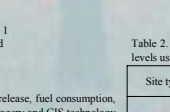


Figure 11. REP relationship to tree mortality.

Table 1. Observed MTCI and REP values for different tree mortality levels, using ENVISAT-MERIS information.

Tree mortality (%)	MTCI	REP (mm)
0 - 20	2.66 - 3.00	722.46 - 723.81
20 - 40	2.31 - 2.65	721.25 - 722.45
40 - 60	2.01 - 2.30	719.78 - 721.24
60 - 80	1.70 - 2.00	718.08 - 719.77
80 - 100	1.20 - 1.69	712.00 - 718.07

Table 2. NDVI and other Chlorophyll indexes obtained for different disturbance levels using Landsat-ETM data

Site type	Tree mortality	NDVI	Index 57	Index 47	Index 54
Fire scars	20-40%	0,183	0,300	0,175	0,131
	40-60%	0,106	0,275	0,154	0,127
	60-80%	0,105	0,279	0,099	0,185
	80-100%	0,039	0,241	0,013	0,229
Harvested sites	Very bad	0,048	0,274	0,055	0,221
	Bad	0,118	0,292	0,123	0,172
	Satisfy	0,233	0,323	0,253	0,076
	Good	0,344	0,370	0,413	-0,054
Undisturbed forests	Coniferous	0,143	0,295	0,338	-0,049
	Deciduous	0,398	0,385	0,472	-0,107
	Mixedwood	0,299	0,352	0,428	-0,090