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Mapping natural forest disturbances in the Western Urals region using remote sensing

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Abstract

The present study investigated the damage caused by forest fires, strong winds and tornadoes to boreal forest of the Western Ural from 2001 to 2015. Long-term series of satellite imagery LANDSAT were used to detect forest disturbance caused by severe storms, tornadoes and large forest fires. The main method of forest disturbance identification was based on short-wave vegetation index (SWVI). Validation of SWVI-based automatized detection results is performed using the satellite images of high and very high resolution (SPOT-5 and WorldView-2). Nearly 70,000 ha of forest areas disturbed by forest fires, severe winds and tornadoes were revealed within the boundaries of the study area (0.6% of the total forested area in the study region). During 2001-2015, damage caused by forest fires was significantly greater than that caused by severe winds and tornadoes. Large forest fires were observed mainly in the north-western part of the study area with pine dominated forests. The damage caused by severe storms and tornadoes was distributed more equally on the study area. However, their frequency was also higher in the northern parts of the region. Identification of several tornado tracks allowed to estimate tornado frequency in the study region. Assessment of species composition and age structure of forests affected by fires and destructive storms, showed that the greatest damage was observed in mature coniferous forests. This caused great damage to regional timber industry.

Key words

Forest fires, Image processing and interpretation, Natural forest disturbances, Remote sensing data, Severe winds, Tornadoes

Introduction

Large areas of boreal forests are annually exposed to destructive impact of extreme natural events (strong winds, forest fires and droughts, heavy snowfalls and freezing rainfalls). They lead to forest sustainability reduction and partial or complete forest disturbance. The damage caused by forest fires, strong winds and tornadoes in some years exceed the amount of logging even in the areas of intensive timber harvesting. In many cases, rapid detection and assessment of damaged forest areas are carried out for effective measure for forest protection and/or restoration (Krylov and Vladimirova, 2011; Gardiner et al., 2010).

The boreal forests cover more than 70% of the area within the administrative boundaries of Perm region (Fig. 1). In this region, forest fires and strong winds are the most significant natural causes of forest disturbance. Large-scale fires in July-August 2010 and a destructive storm of July 18th, 2012 have greatly damaged the forest resources (Vetrov and Shikhov, 2013). The frequency of such extreme events may increase in future due to changes in the regional climate.

Satellite monitoring is the most effective tool for identifications of forest loss different spatial scales (Bartalev et al., 2007; Hansen et al., 2013; Krylov and Vladimirova, 2011; Petukhov and Nemchinova, 2014). Remote sensing data are used to detect and map the forest disturbances caused by forest fires and severe winds (Bartalev et al., 2007; Jonikavi□ius and Mozgeris, 2013; Wang et al., 2010), to determine the forest damage (Bartalev et al., 2010, Cocke et al., 2005; Kurbanov et al., 2012; Peterson, 2000), and to estimate the role of extreme climate events that may influence forest resources in different eco-regions of the Earth (Schlyter et al., 2006; Hilker et al., 2009; Özkan et al., 2015; Sowmya and Somashekar, 2010).

Satellite images can be successfully used not only to detect the forest disturbance, but also in the study of natural disasters that have caused forest damage. Several studies related to evaluation of hazardous weather phenomena intensity, according to the windfall disturbances in the forests have been carried out. The tornado tracks are accurately determined satellite images. Also, the high resolution satellite images are used for the near-surface wind speed distribution modelling on the tornado exposed area (Beck and Dotzek, 2010; Jedlovec et al., 2006; Peterson, 2000). Selection of satellite images for forest loss identification depends on the required spatial and temporal resolution, as well as on the features of studied forest disturbance type.

The forest disturbance assessment at the global and continental scale is based on low-resolution MODIS and SPOT-Vegetation data (Bartalev *et al.*, 2007; Fraser *et al.*, 2000), LANDSAT data are more preferable for regional forest loss assessments (García-Haro, 2001; Baumann *et al.*, 2014; Petukhov and Nemchinova, 2014). Their advantages are the favorable combination of spatial, spectral and temporal resolution, the presence of the archive for a long time period (over 40 years) and free availability of data. These data have already past the geometric correction.

In light of the above, the present study was carried out to evaluate the damages caused by forest fires, strong winds and tornadoes to boreal forest of the Western Ural from 2001 to 2015. Besides, the features of spatial distribution of large-scale forest fires and forest windfalls disturbances were also investigated.

Materials and Methods

The satellite imagery LANDSAT-5 (sensor TM), LANDSAT-7 (sensor ETM+) and LDSM-8 (sensor OLI/TIRS) for the period 1999 to 2013 were used as initial data for the study. Also, high resolution data (SPOT-4, SPOT-5 and World View-2) for the period 2011 to 2013 were used. Automatized identification of deforestration (forest harvest, burned area and wind damage) were implemented by LANDSAT images. High resolution images were used for validation of the results of forest disturbed area identification.

The assessment of forest loss area (without attribution of disturbance type) has been made on the principles of short-wave vegetation index SWVI difference. The efficiency of NDVI (Normalized difference vegetation index) and changes in SWVI (Short-wave vegetation index) using Multivariate Change Detection methodology was due to the fact that on disturbed forest area along with a decrease in photosynthesis and the reflectance in the near infrared (NIR) spectrum, there is a significant increase in the average reflectivity in short-wave infrared (SWIR) spectrum. This increase was determined by decrease in moisture content in leaves (needles). SWVI was calculated by the following formula:

$$SWVI = (NIR - SWIR) / (NIR + SWIR)$$

where, *NIR* is the spectral brightness in the near infrared zone, *SWIR* is the spectral brightness in the shortwave infrared zone. To identify the forest disturbance area, a threshold criterion was used. The threshold value was determined by experts based on the image statistics,

Fig. 1 : Location of the study region

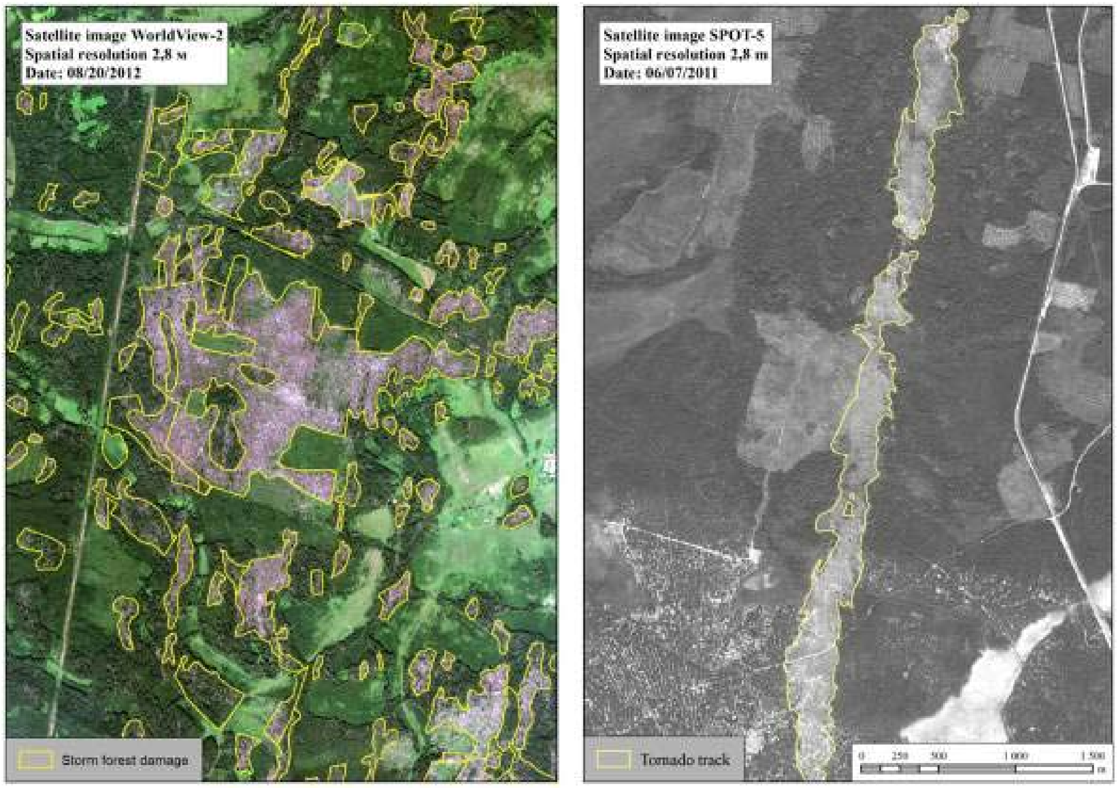

Fig. 2 : Forest windfall caused by severe storm July 18th, 2012(a) and EF3 tornado June 7th, 2009(b)

depending on the season of satellite imagery and cloud cover. Calculations were performed within the pre-created forests mask. The obtained results were subjected to smoothing algorithm, filtered by minimum area threshold value, and were automatically vectorized.

The forest disturbance type were determined empirically. Natural disturbances were divided into three types: burned forested areas, forest windfalls caused by strong winds and tornado tracks.

To determine burned forested areas, the data archives MOD14 MODIS Fire Product for the period since 2001 were used (Justice *et al.,* 2002). The data about thermal anomalies were obtained from FIRMS (Fire Information for Resource Management System) provided by NASA.

A geometric shape (a considerable length, the lack of right angles) and the object texture were the most important characteristics while separating the forest windfalls and cutting harvest. A forest windfall disturbance length usually exceeded the width 3-10 times (for the windfalls caused by strong destructive winds) or 20-50 times (for the windfalls caused by tornadoes). In addition, the forest windfalls caused by strong destructive winds were characterized by a complex

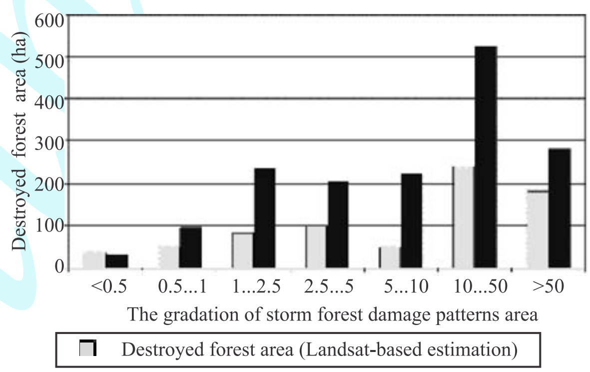

Fig. 3 : Distribution of forest windfall area, estimated by Landsat and

mosaic structure, which was determined by the terrain and forest species composition (Fig. 2).

The panchromatic and multi spectral SPOT 4/5 images for 2011-2013 were used for sample validation of forest disturbance identification results. Total validation was carried out at the Kochevo forestry (the North-West of Perm region). The investigated area was 250 km^2. This territory was strongly affected by severe storm on July 18th, 2012. The multi spectral imagery World View-2 (the spatial resolution of 2 m) has been used for the investigation. The forest windfall patterns have been manually digitized from this imagery (in general 506 sites on a total area of 1596 ha). The total area of forest disturbance at this plot was automatically identified based on LANDSAT image is 1.9 times less than the actual area defined by the image World View-2. It had less to do with the skipping of small forest damage plots, much to underestimation of the damaged area. This corresponded to the results presented in the article (Koroleva and Ershov, 2012). The average size of the forest disturbance pattern defined with the image WorldView-2 was 3.1 ha., and with the image LANDSAT-5 it was 1.7 ha. The forest windfall plots distribution on area gradation is shown in Fig. 3.

Results and Discussion

The total area of forest disturbance caused by extreme natural events on the study territory during the period 2001-2015 was about 70,000 ha (0.6% of the total forested area). 42,200 ha was affected by large forest fires, and 27,000 ha were disturbed by severe winds and tornadoes. In total, 18 cases of significant forest windfalls and 39 cases of large forest fires (burned area >100 ha) were identified in the present study area (Table 1).

Strong destructive winds (a common special case microburst) and tornadoes were the cause of forest disturbance in the study area. Large-scale forest windfalls were caused by strong destructive winds in 18th July, 2012 (6 plots of forest disturbance on the total area of about 24,000 ha). The damaged forest areas represented complex mosaic of several large (10-150 ha) and many small plots of total forest disturbance (Krylov and Vladimirova, 2011; Gardiner *et al.,* 2010). Large-scale forest windfall occurred at six plots in the north-western and north-eastern parts of the region, which was one of the main sources of timber for the regional forest industry. Mature dark-coniferous forests and mixed pine-birch forests were affected by severe wind. This case of severe convective storm and their damage is more precisely described by (Vetrov and Shikhov, 2013). The researches revealed mass windfalls in the northern forests of the Perm region by means of remote sensing. The windfalls were caused by severe gusts which occurred in the Kama basin region on July 18, 2012. The collected data were used to detect the areas of maximal wind speed.

The outbreak of tornado on 07.06.2009 significantly damaged the forest resources. They were passed on the north-western part of the study area. The total tornado track length exceeded 90 km., the forest windfall width was 100 to 600 m and the total area of forest disturbance was about 2,500 ha.

Other revealed cases of forest windfalls were a local type and the mainly caused by strong local destructive winds (wet microburst) with the wind speed more than 30 m sec^{-1}. In most cases, strong destructive winds on the study area did not cause significant forest disturbance.

The spatial distribution analysis of forest windfalls revealed that they most by occurred in the northern part of the study area in the middle-taiga landscape subzone. In this region there are large areas of mature and overripe spruce-fir and mixed forests susceptible to strong winds impact (Fraser *et al.*, 2000). .

The geometrical characteristics of significant forest windfalls that occurred on the study territory in 2001-2014 are shown in Table 2, and their spatial distribution is shown in Fig. 5 (Kurbanov *et al.*, 2012). Revelation of 7 tornado tracks

Table 1 : Large forest fires and destructive storms impact on forest resources of the Western Ural region

Year	The number of large forest fires (identified by the satellite monitoring data)	The burned forested area (estimation by LANDSAT images (ha))	The number of severe storms and tornadoes, caused forest damage	The forested area damaged by severe storms and tornadoes ((estimation by LANDSAT images (ha))
2001	5	10 540	0	0
2002	0	0	0	0
2003	0	0	1	449
2004	0	0	1	227
2005	1	137	0	0
2006	0	0	2	243
2007	1	112	1	198
2008	0	0	1	60
2009	0	0	4	2566
2010	31	31 200	0	0
2011	1	180	0	0
2012	0	0	1	23450
2013	0	0	0	0
2014	0	0	1	590
2015	1	850	1	359

Table 2 : Geometrical characteristics of storms forest disturbance areas identified by multi-temporal satellite images

Storm date	Storm type	Damaged forested area (ha)	Length of damaged area (km)	Maximum width of damaged area (km)
08/08/2003	Microburst	449	13.7	0.90
Undefined	Tornado	227	16.0	0.30
Undefined	Microburst	117	5.0	0.60
Undefined	Tornado	126	14	0.25
08/16/2007	Microburst	198	6	0.4
08/30/2008	Tornado	60	5	0.2
06/07/2009	Tornado outbreak	141	14	0.3
		1263	42.0	0.60
		124	8.0	0.30
		593	20.0	0.70
		445	18.0	0.60
07/18/2012	Severe storm	723	18	5.5
		8550	47	17
		9300	85	19
		3050	20	11.5
		835	18	6.5
		990	30	2
08/17/2014	Microburst	590	18	2.5
06/16/2015	Microburst	359	14	2

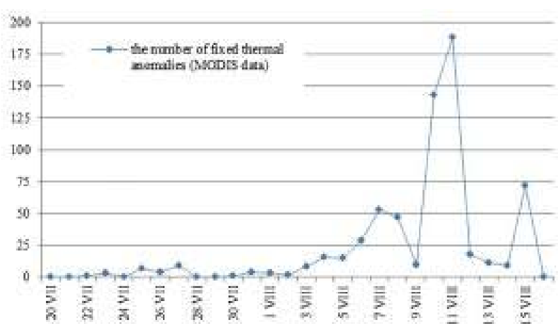

Fig. 4 : Number of thermal anomalies detected by MODIS sensor, fire-dangerous period of the 2010 summer

is of particular interest. This phenomenon allowed to revise the existing assessment of the tornado frequency rate in the northern part of the Western Urals, and to classify the present territory to high tornado hazardous zone. Maximum tornado intensity in this region might be up to EF3 category (EF3 tornado was recorded in June 7, 2009). At the next stage the obtained experience and the method of multitemporal image analysis could be used to map the tornado frequency rate across the boreal forest zone of the European part of Russia.

The Western Ural territory was characterised by relatively low natural forest fire danger. That was due to territory abundant moistening and mainly covered by mixed forests with a predominance of spruce and birch trees. Large forest fires were observed in the Western Ural in the case of long summer heat waves such as summer 2010, and a lesser degree in July, 2001 (Table 1). The largest forest fire over the lest 15 years (more than 6,300 ha burned area) was observed

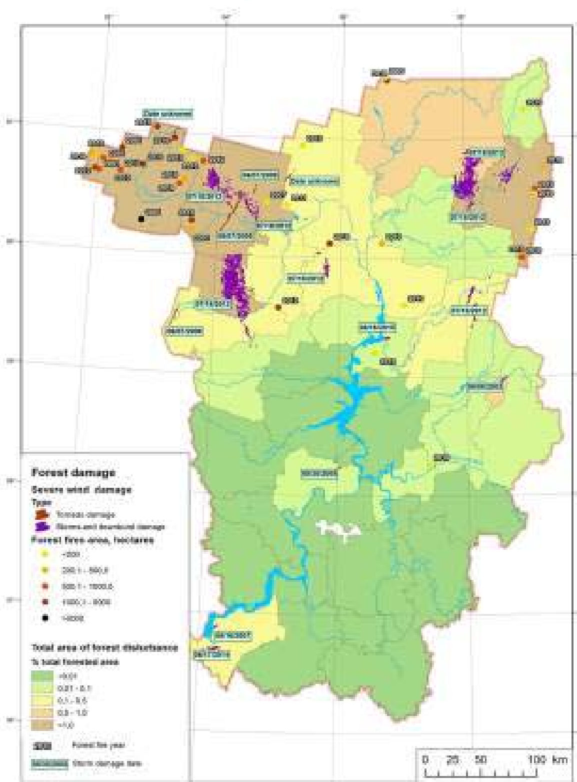

Fig. 5 : Estimated area of forest damage caused by large forest fires, severe storms and tornadoes in 2001-2015

in July, 2001. Species composition and age structure of forest massive are shown in Table 3. Large fires during the summer

Table 3 : Species composition and age structure of forest massive disturbed by fires and destructive storms. (total percent of disturbed area)

Forest type	Forest fires damage	Forest windfalls
Old-growth dark-coniferous forest	6.8%	29.3%
Old-growth pine forest	33.8%	6.1%
Mature and middle-aged mixed forest with a predominance of spruce and fir trees	13.9%	26.5%
Mature and middle-aged mixed forest with a predominance of pine trees	4.4%	5.0%
Mature and middle-aged mixed forest with a predominance of birch trees	0.4%	9.1%
Mature and middle-aged deciduous forest	0.4%	7.7%
Sparse young pine forest	10.4%	1.7%
Sparse young deciduous forest	8.6%	9.6%

2010 covered 4,500 ha.

2001 and 2010 summer were characterised as anomalous forest fire risk. During the summer 2010, heat wave, extreme forest fire danger was observed across the study area. Large forest fires were observed from July 24 to August 24, 2010 (Bartalev *et al.*, 2010). They were caused by long period of abnormal hot and dry weather caused by dominance of a blocking anticyclone. The average temperature exceeded the normal one by 5-7°C, there was a lack of sufficient precipitations, but lightning storms were regularly observed during that period. Thunderstorms were the main cause of many large forest fires during the summer 2010 in the Western Ural. August 10-11 was characterised by maximum fire risks when more than 40 fires simultaneously happened on the investigated territory. Some of them were large enough (Fig.4).

Large forest fires were also observed from July 17-27, 2001 in the north-western part of study area. High fire danger was caused by long period of dry and hot weather on the European part of Russia at the background of blocking anticyclone. Five large forest fires occurred in total area of 10,500 ha.

The Veslanskaya lowland in the north-west of the study region was characterised by a large number of forest fires and their affected area. There were 19 cases of large forest fires during 2001-2010 and their affected area was 24,600 ha. (Fig. 5). High frequency rate of forest fires at that territory was due to high initial pine forest distribution on the sandy soil and high natural fire danger. The far distance from Ural mountains also affected the fire risks as there was less precipitation in summer than in eastern territories. Difficult accessibility prevent early fires detection and fighting.

The forest vulnerability to fires and strong wind was determined by species composition and age structure. The forest types most vulnerable to dangerous natural phenomena were revealed on the basis of the forest species composition and age structure map of the study area. The map was based on Terra MODIS imagery was created during different seasons. Most cases of large fires in the Western Urals occurred in pine forests, and both mature and young stands were characterised by high susceptibility. Many areas are regularly affected by forest fire, that explained the high proportion (21.2%) of plots with open forests surrounded by burned forest areas.

Forests with predominance of dark coniferous species were primarily affected by severe wind (more than 50% of the total area of forest windfalls). As these forests are of importance for the timber industry in the region, the damage caused by windfalls for the region forestry is comparable to the damage caused by forest fires (Petukhov and Nemchinova, 2014).

The forest resources damage caused by forest fires and windfalls in Western Ural from 2001 to 2015 was assessed in this study. The zone a high frequency rate of large forest fires has been revealed in the northwest of the region, which correlates with the spread of pine forests. 7 cases of windfalls caused by tornadoes have been revealed. This fact allows us to revise the existing assessment of the tornado frequency in the northern part of Perm region.

The research is identifying and discriminating natural forest disturbances in a region much underrepresented in the non-Russian science community. The relevance of the study is confirmed by usage of up-to-date satellite imagery and gaining impressive results on forest damage due to windfalls and forest fires in the study region.

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