USING REMOTE SENSING TO ASSESS RUSSIAN FOREST FIRE CARBON EMISSIONS

A. S. ISAEV [1], G. N. KOROVIN [1], S. A. BARTALEV [2], D. V. ERSHOV [1],
A. JANETOS [3], E. S. KASISCHKE [4], H. H. SHUGART [5], N. H. F. FRENCH [6],
B. E. ORLICK [7] and T. L. MURPHY [7]

[1] *Center of Problems of Ecology and Productivity of Forests (CEPL), Russian Academy of Science, Novocheriomuskinskaya Str. 69, 117418 Moscow, Russia*
E-mail: isaev@cepl.rssi.ru
[2] *Space Application Institute/Joint Research Center, CCR/TP 440, I-21020 Ispra (VA), Italy*
[3] *World Resources Institute, Washington, D.C., U.S.A.*
[4] *Department of Geography, University of Maryland, 2181 Maryland, LeFrak Hall, College Park, MD 20742, U.S.A.*
[5] *Department of Environmental Sciences, University of Virginia, Clark Hall, Charlottesville, VA 22903, U.S.A.*
[6] *Altarum, PO Box 134001, Ann Arbor, Michigan 48113-4001, U.S.A.*
[7] *U.S. National Imagery and Mapping Agency, Washington, D.C., U.S.A.*

Abstract. Russian boreal forests are subject to frequent wildfires. The resulting combustion of large amounts of biomass not only transforms forest vegetation, but it also creates significant carbon emissions that total, according to some authors, from 35–94 Mt C per year. These carbon emissions from forest fires should be considered an important part of the forest ecosystem carbon balance and a significant influence on atmospheric trace gases. In this paper we discuss a new method to assess forest fire damage. This method is based on using multi-spectral high-resolution satellite images, large-scale aerial photography, and declassified images obtained from the space-borne national security systems. A normalized difference vegetation index (NDVI) difference image was produced from pre- and post-fire satellite images from SPOT/HRVIR and RESURS-O/MSU-E images. A close relationship was found between values of the NDVI difference image and forest damage level. High-resolution satellite data and large-scale aerial-photos were used to calibrate the NDVI-derived forest damage map. The method was used for mapping of forest fire extent and damage and for estimating carbon emissions from burned forest areas.

1. Introduction

Forests are an important element of the biosphere and a source of many forest products. Balanced use of forests correlates strongly with type of business activity and careful management of forest ecosystems. New data and non-traditional approaches are needed for monitoring forest condition and dynamics under natural and anthropogenic influences. Data quality can be significantly improved using remote sensing resources and GIS technologies. This results in a more accurate quantitative assessment of dynamic processes in forests, such as large-scale natural events, human activities, and long-term climate change. More accurate assessments

Climatic Change **55:** 235–249, 2002.

would help our understanding of the interaction between forest ecosystems and the atmosphere.

Our research is a result of collaboration between Russian and American specialists who investigated the advantages of using satellite images for forest monitoring. The project intended to assess the utility of remote sensing for wildfire mapping, develop methods for measuring carbon emissions associated with forest fires, and calculate the boreal forest carbon budget.

Earlier research shows that information from satellite images can be used to assess a number of important forest characteristics. Differences in these characteristics reflect large-scale changes in forest ecosystems [1, 2]. We believe that remote sensing from civilian satellites can become the key technology for measuring forest carbon budget parameters. Civilian systems can be used to map forests, detect damage and assess fire boundaries and magnitude of fire, and monitor the regeneration of forest vegetation and dynamics of carbon pools. The need to calibrate forest stand parameters, best performed using ground data, is a crucial factor, which limits the potential of carbon dynamic assessments based on commercial satellite images. Very high-resolution (up to 1 meter) images open a new possibility here. This includes declassified images obtained from the U.S. and Russian national security systems. High-resolution images can be successfully used to calibrate forest parameters, which are necessary for calculation of carbon pools based on commercial satellite images.

2. Forest Fires and their Impact on Forest Ecosystems

2.1. FOREST FIRES AND CARBON EMISSIONS

Each year, 10–35 thousand forest fires covering 0.5–5.3 million hectares (ha) are detected in the actively protected part of the Russian forest. According to State Forest Inventory data, 16 million ha of area in actively protected zones are classed as burned or destroyed forest. Forest in the northern regions of Siberia and the Far East are not covered by a regular forest fire monitoring service, but State Forest Inventory data has recorded 12.4 million ha of burned or disturbed forest area in this territory. This estimate illustrates the high flammability of north taiga and forest-tundra, and the high fire damage in these ecosystems. The total annual area burned in Russian boreal forests is measured at 2–5.5 million ha, including 0.4–1 million ha of high-intensity, stand-replacing fires [3]. Some authors using indirect methods estimate larger amounts of wildfire annually in Russian forests – up to 10–12 million ha [4].

Organic material burned during forest fires result in an annual release to the atmosphere of 15–45 mega-tons of carbon (Mt C) in a form of carbon oxides and soot. Additionally, 20–53 Mt C is released annually as a result of destruction and decomposition of unburned organic material after fires. Total carbon emissions from fire-disturbed Russian boreal forests are estimated at 35–93 Mt C per year. This is equivalent to 128 to 340 Mt of CO_2 released annually into the atmosphere. Using indirect assessments of forest wildfires, some authors estimate annual Russian fire emissions at more than 150 Mt C [5, 6].

2.2. ASSESSING FIRE IMPACT ON FOREST ECOSYSTEMS

Remote sensing can significantly improve the existing forest fire monitoring system that is based on ground measurements and aerial detection methods. Remote sensing can solve such problems as the following:

- Detecting large forest fires and assessing burned areas.
- Assessing the structure of burned areas and the damage level of forest vegetation.
- Assessing the consequences of fire and forest regeneration in the burned areas.

The first of these problems is easily solved because remote sensing can effectively cover more area then aerial photos and ground survey methods. Large forest fires (with an area of more than 200 ha) are responsible for 95% of the Russian boreal forest area burned each year, so detection and mapping of large fires is important. The results of multiple studies and experience in using satellite images from meteorological (NOAA, Meteor) and resource (Landsat, SPOT, RESURS) satellites demonstrates the ability to detect large forest fires and burned areas [7, 8]. The high frequency of repeat passes of the meteorological satellites allows the possibility of receiving the latest information about the parameters and location of large forest fires. Further surveys of these fires and burned areas are then possible with the higher resolution but less frequent resource satellites.

We used high resolution (30 m) images from resource satellites to map forest fire boundaries and to further categorize the burned area into different types of fire (crown, ground) with different damage levels for aboveground and ground vegetation. Comparison of the wildfire boundary with forest maps allows assessment of pre-fire structure and condition of forest vegetation. The post-fire condition of forest vegetation was assessed from high and very high-resolution satellite images (up to 1 m resolution). The results of our investigations have shown that it is possible to distinguish the major land categories and parameters of the forest using remote sensing data received from Russian and U.S. national security systems [1, 2].

Quantitative information about the pre-fire and after-fire structure and condition of forest vegetation can be further used to assess dominant tree species, estimate stocks and consumption of forest organic material, and to assess post-fire mortality. This information is needed for estimating the fire and post-fire carbon emissions from the burned area.

3. Objectives of the Study and Existing Information

We studied the East Siberian burned stands in the Taseevsky region of Krasnoyarsk (the lower Angara River region). Over the past 50 years, the forests of this region have been under extensive industrial use and have been frequently damaged by fires and insects. Natural and human impacts made a significant change in the condition, species, and age structure of the forest and on its resource and protection role. The Usolsky leskhos (forest unit), located in the lower Birusa River basin, was the main area of our research. We studied a recently burned area, caused by a large May 1997 fire, which covered 2467.2 ha of the forest. The center of forest fire damage was located in an area with large stands of pine and birch – an area of 30–60 year old clearcuts. The burned area is comprised of a mosaic of forest damage, growing conditions, species and age composition, and forest floor organic material. We used remote sensing data from civilian satellites, national security systems, and aerial photography to assess the utility of these systems to measure the level of forest fire damage. We also used the following existing information:

- 1992 (pre-fire) forest inventory data;
- Multi-spectral SPOT (May 1995, pre-fire) and RESURS-O/MSU-E (August 1997, post-fire) satellite images of the area;
- 1998 1:10000 aerial photographs;
- 1998 1:2500 routing aerial photographs (used for training samples);
- 1998 ground survey data of burned area, including inventory data of 16 sample plots and results of study of the samples of forest fuel materials.

The following information was used to estimate forest vegetation carbon pools, their year-to-year dynamics, and fire emissions:

- Forest phytomass and production database [9];
- Yield tables for normal forest stands of the dominant species [10];
- Tables of conversion coefficients between the volume of stem wood and fractions of phytomass in forest stands of various tree species and age classes [11];
- Table of coefficients for allometric equations, which allows calculation of the mass of young stands and natural regeneration [12].

4. Methods

We surveyed the burned stands following the current official forest inventory procedure [13]. Additionally, we developed special methodological procedures to describe the structure and stocks of forest fuel materials, their consumption during forest fires, and the degree of fire damage of sub-canopy forest vegetation, litter, and soil humus.

We separated the burned areas of forests into two groups: *completely burned* (dead stands) and *damaged* (stands damaged by fire) areas. We collected the following information for the *completely burned* areas: forest inventory data of the dead stand and type of fire (crown, ground, underground). For the *damaged* forest stands we collected the forest inventory data for alive and dead parts of the stand separately. We collected inventory and fire damage data from sample spots located in the burned, damaged, and undamaged areas, which had similar forest inventory data. We assessed fire damage in sub-canopy layers of forest vegetation, the live part of floor cover, and litter to supplement regular forest inventory data. We took the samples of the live portion of forest floor cover and litter in representative sites to assess the structure and stocks of fuel materials. The main forest characteristics used for calculating ground fuel materials were: mean depth of the top floor cover layer (cm), density of the forest floor material (kg/m^2), distribution of floor cover stock derived by fractions (glue, grass-scrub level, detritus), and thickness of litter. We also performed a forest inventory of the burned area and made qualitative assessments of stand condition using the ground data and large-scale aerial photographs. This data was necessary to assess fire carbon emissions.

4.1. GIS DATABASE OF SAMPLE AREAS

A GIS database of sample areas was created from the research data, pre-existing forest inventory data, SPOT and RESURS satellite images, and large-scale aerial photographs. The database formats are compatible with the formats of Arc/Info and ERDAS. The following layers were included in the database:

- Vector coverages of stand boundaries with the attributes of 1997 forest inventory data for the burned areas.
- Vector coverage of stand boundaries according to 1992 inventory with the attributes of stands inventory description.
- Vector coverage of the centers of sample plots, located in the burned area with the attributes describing the level of damage and flammable woody material stocks.
- Vector coverage of the location of sample large-scale aerial photographs of the burned area of forest, taken in 1998.

The GIS layers were combined with a cartographic base map and with multispectral SPOT and RESURS-O/MSU-E satellite images of the burned area.

4.2. ASSESSING THE LEVEL OF FOREST FIRE DAMAGE

The level of fire damage was used as an input parameter to calculate fire carbon emissions. We defined the level of fire damage as a fraction of forest canopy area, which is covered by the crowns of dead trees, destroyed by wildfire.

We assessed the level of forest fire damage using multispectral satellite images, one of which was taken before and the other after the fire. We also used the sample data from the test plots. For the first step we generated sets of parameters of spectral brightness correlated with the area of green vegetation using each of the satellite images. For spectral brightness we used the normalized differential vegetation index (NDVI). The effectiveness of this index in vegetation mapping and in assessment of forest fire damage has been shown in a number of studies [14–16].

We used the computed pre-fire NDVI (t_1) and post-fire NDVI (t_2) to generate a difference image ΔNDVI, where:

$$\Delta\mathrm{NDVI} = \mathrm{NDVI}(t_2) - \mathrm{NDVI}(t_1).$$

The difference image was used to locate burned stands and to assess damage level. The first assessment was done using ΔNDVI distribution diagrams to determine the set of pixels in the fire-damaged area $\{C_j\}$. The level of tree stand damage was estimated in the second step of the analysis. Here we used the set of $\Delta\mathrm{NDVI}_j$ values and a representative sample (a training set) of data describing the forest damage level $\{D\}$, which was a subset of $\{C_j\}$. This training set was generated from the whole set of sample plots using the large-scale aerial photography and the national security systems data. We selected the test areas so that the corresponding NDVI values would cover their entire spectrum as uniformly as possible. For each test plot i, we used the level of forest damage D_i and correspondent average value of $\Delta\mathrm{NDVI}_i$. These parameters were used to produce the regression equations $D_i = f(\Delta\mathrm{NDVI}_i)$ and to generate the calibration function. This function was then used to analyze the difference image and to compute an estimate of the level of damage of the forest stand.

4.3. ASSESSING FIRE CARBON EMISSIONS

We measured the amount and chemical composition of carbon released during biomass combustion. The total burned biomass was determined as a function of wildfire area, structure and stocks of forest fuel materials in this area, the type and intensity of combustion, and the fraction of flammable materials burned for each combustion type and intensity [3, 17, 18].

The area of fire, type, and intensity of combustion were determined from the analysis of remote sensing data. Pre-fire structure and volume of flammable materials were estimated from the forest inventory data. The fraction of flammable materials burned for each combustion type and intensity were determined from experimental data of the burned fractions of live floor vegetation, of vegetation of forest and shrub levels, and of forest litter.

We assessed the structure and volume of forest fuel materials for each homogeneous forest stand, taking into consideration the species and age structure of the forest stand, vertical structure of the forest vegetation, and the role of each vegetation layer in combustion. We identified six levels of forest fuel materials: forest canopy (W1); sub-canopy (W2); dead wood (W3); floor cover with detritus

(W4); litter (W5); soil humus and peat (W6). From the analysis of structure and volume of forest fuel materials of the study area, we constructed a local database of pre-fire forest fuel materials and a map of forest fuel materials volume per hectare. This map was used in further research.

We identified zones of potential crown fire spread in the two following steps. First, for each forest stand, we analyzed the structure of forest canopy with respect to potential fire conductance during a crown fire and the potential of the other vegetation layers to support crown fire. Second, we found the boundaries of areas and zones potentially burned by crown fire. We assumed that an area could be burned by a crown fire under the following conditions:

- The dominant tree species in the area (forest inventory unit) is a conifer;
- Forest crown density is at least 0.3 for young stands and at least 0.4 for mature stands;
- Middle-aged and mature stands have a multiple layer structure and/or coniferous understory.

Adjacent areas meeting these requirements were combined to generate zones that potentially could burn in a crown fire. Areas which did not meet the requirements were combined into zones that potentially could burn in a ground fire. As a result of these procedures, we generated a map of potential areas of crown and ground fire which divided the study area according to fire type.

We estimated the type and intensity of fire by overlaying two maps: the map of potential areas of crown and ground fire and the map of degree of fire damage to forest vegetation.

We assumed that zones actually covered by crown fires are determined by the intersection of potential area of crown fire and area of very high level of forest fire damage with 20% or less live trees. We also assumed that zones of intensive ground fire include the areas of very high level of fire vegetation damage (excluding potential areas of crown fire) and the area with medium level of fire damage with 20% to 40% live trees. Areas with medium level of forest fire damage with 40% to 70% live trees were considered as a zone of medium intensity ground fire. Areas with small level of fire damage with 70% to 90% live trees were considered as a zone of low intensity ground fire. Finally, we classified stands with less than 10% of dead trees into a category of stands with minor damage from forest fires or undamaged.

We used pre-fire mass of flammable forest materials and the fraction of burned phytomass to find the organic mass combusted in each of the burn areas. The fraction of phytomass for each layer (component) of flammable material was determined as a function of fire (combustion) type and intensity:

$$Q_p^{(l)} = \sum_{r=1}^{R} W_r \beta_{rp}^{(l)} .$$

Here, W_r – mass of layer (component) r of pre-fire flammable material, t/ha; $\beta_{rp}^{(l)}$ – fraction of layer (component) r of forest fuel material, burned in a fire of type l and intensity p; $Q_p^{(l)}$ – mass of organic materials burned in fire type l and intensity p, t/ha.

Numerical values of $\beta_{rp}^{(l)}$ coefficient were derived based on experimental data for different types and intensities of fires in various forest site conditions of the taiga zone.

The intensity of fire carbon emissions in each of the burned areas was found by multiplication of the mass of combusted organic materials by its carbon content. The total mass of combusted organic materials and the total amount of carbon emission were found by summing the correspondent values for each of the burned areas. From these results, the maps of forest fuel materials and of the volumes of fire carbon emissions were generated.

5. Results and Discussion

5.1. ASSESSING FOREST FIRE DAMAGE

We assessed forest fire damage using an NDVI difference image generated from SPOT and RESURS-O/MSU-E satellite data (Figure 1). We found a range of significant NDVI difference [–0.56 to –0.12] which describes fire-related change of spectral characteristics. These data allowed us to determine patterns of stands affected by fire, and to select test plots for comprehensive study of the damaged stands.

The second step of our research included calibrating civilian satellite images with data from the national security systems and large-scale aerial photographs. One expert group assessed tree stand disturbance in the test plots using standard categories of trees fire damage described above. The second group performed the same task independently using large-scale aerial photographs. Comparison of their results shows that the assessment of tree stand damage made with the large-scale aerial photographs are in a good agreement ($R^2 = 0.76$) with the assessment made with the very high-resolution satellite photographs. The discrepancy between the results can be explained by errors in co-locating the test plots. These errors are related to the high heterogeneity of tree stand structure.

Our assessment of tree stand damage was also used to generate the calibration function which connects NDVI difference to the level of stand damage in the burn area. Figures 2a,b presents regression plots of the degree of stand damage and NDVI difference, using data from the national security systems and from large-scale aerial photography. Since both regressions show rather high linear correlation between the degree of stand damage and ΔNDVI ($R^2 = 0.82$ and $R^2 = 0.89$), it is possible to use the resulting equations as calibration functions for determining stand damage. Large-scale aerial photographs give the highest correlation between

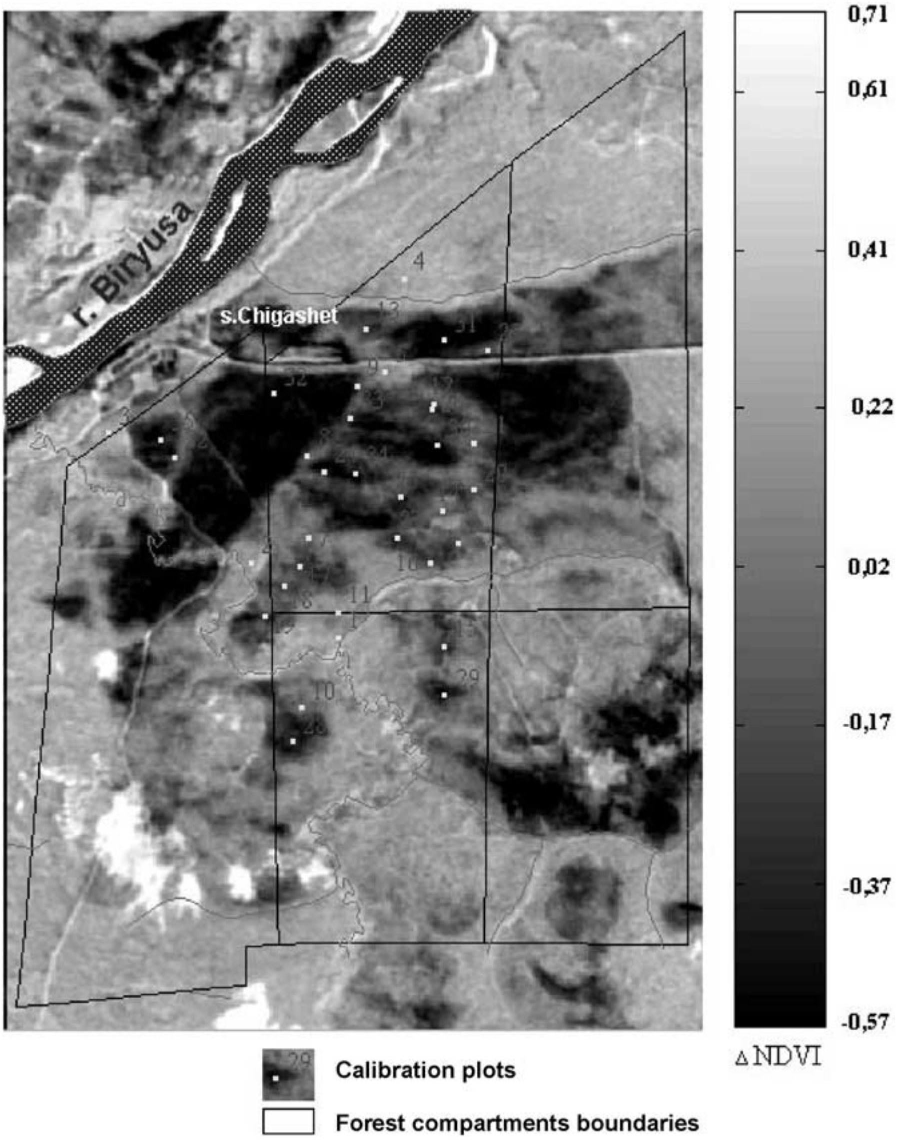
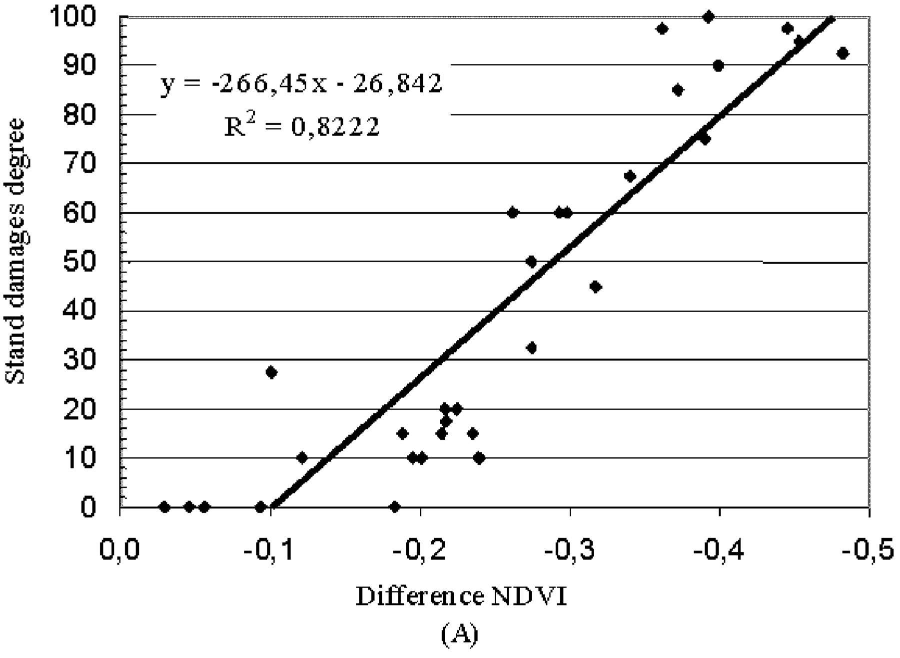


Figure 1. NDVI difference image with the locations of calibration plots for assessing fire damage.

these two parameters. Because of that, we can use the large-scale aerial photographs to comparatively assess the data from national security systems. Based on the results of this research, we believe that the near-linearity of the correlation between the degree of tree stand damage and ΔNDVI is general in scope and can be used to estimate the actual parameters of stands damaged by fires.

The derived linear regression equations let us reconstruct the levels of stand fire damage for the entire burn area and to map fire damage. Comparison of the maps of



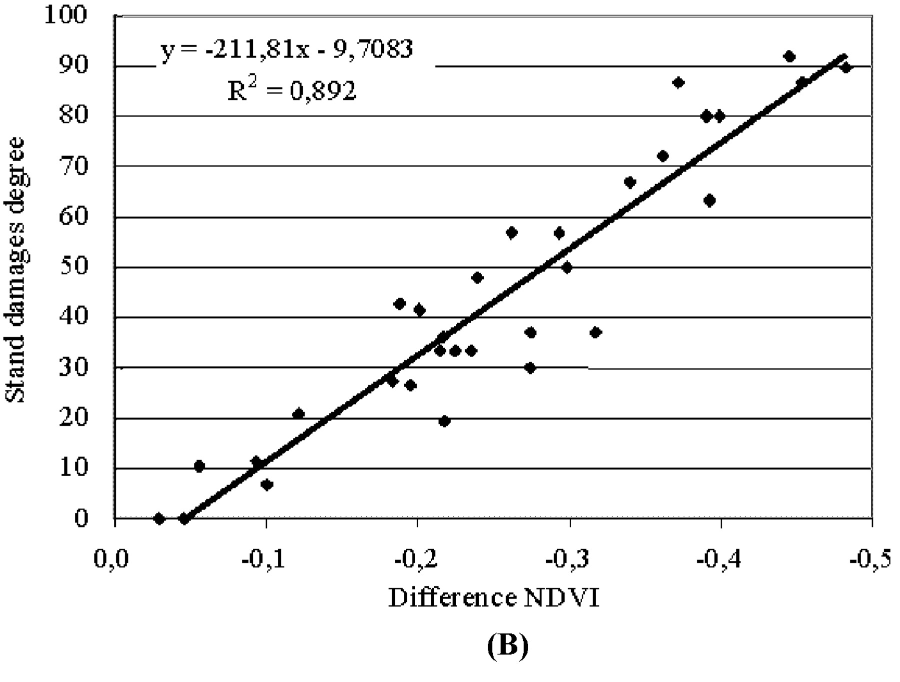


Figure 2. Regression plots and equations connecting NDVI difference to degree of stand damage derived from (a) aerial photographs and (b) national security systems.

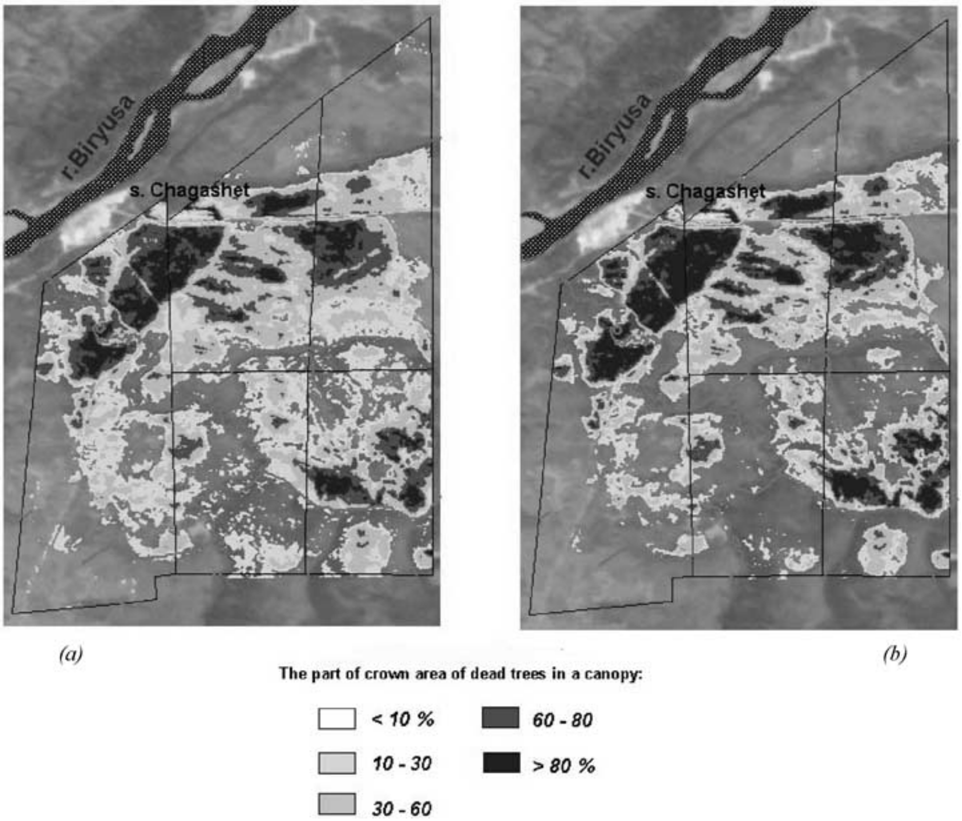


Figure 3. Burn severity assessment using the NDVI difference image in combination with results of (a) aerial photographs and (b) national security data interpretation.

forest damage generated using the data from two independent sources shows good qualitative agreement (Figures 3a,b). The highest disagreement in damage levels can be found in least-damaged stands (11%–30%), which were mis-classified as undamaged stands in the interpretation of the national security data.

5.2. MAPPING FIRE TYPE AND INTENSITY

We determined fire type and intensity by overlaying tree stand damage maps that we generated using (a) the large scale aerial photographs and (b) very high resolution satellite images with the map of potential ground and crown fires (Figure 4). The latter map was built using the GIS layer which included vector coverages of stand boundaries, attributes of forest inventory of the fire area, and structure and mass of forest fuel materials. We separated the potential zones of crown fire using the established selection criteria. The superposition of stand damage maps with the potential areas of wildfire gave us a fire map that showed spatial distribution of fire types and intensity. The crown fire areas accounted for 178.5 ha (7%) of the total

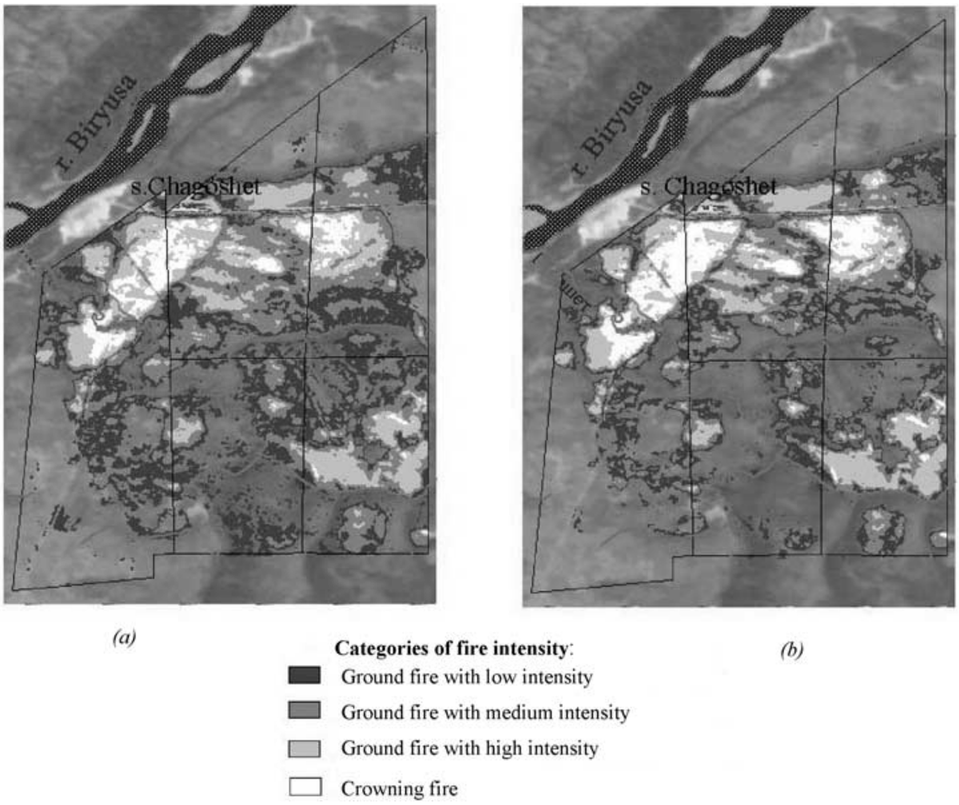


Figure 4. Maps of type and severity of fire as result of joint satellite image processing in combination with: (a) aerial photograph, (b) national security data.

study area; 5,333 ha (22%) were attributed to high-intensity ground fires; 8,418 ha (34%) were attributed to medium-intensity ground fires; and 9,136 ha (37%) were attributed to low-intensity ground fires.

5.3. ASSESSING BURNED BIOMASS AND FIRE CARBON EMISSIONS

In conjunction with mapping potential crown and ground fire zones we generated a database and corresponding map of the structure and stocks of pre-fire and post-fire fuel materials. We used this database to calculate fire carbon emissions.

The mass of forest crowns that conduct crown fire was derived from the mass of stem wood using the conversion coefficients. The mass of sub-canopy layers was found using allometric equations. The mass of live floor vegetation and litter was extracted from a forest phytomass and production database. The combusted fraction of forest fuel materials for each fire type and intensity was determined from previous experiments and the official forestry handbook [20]. We assumed that the combusted organic materials contained 50% carbon. Carbon emissions per ha of burned area were estimated for each fire type and intensity zone (Figure 5).

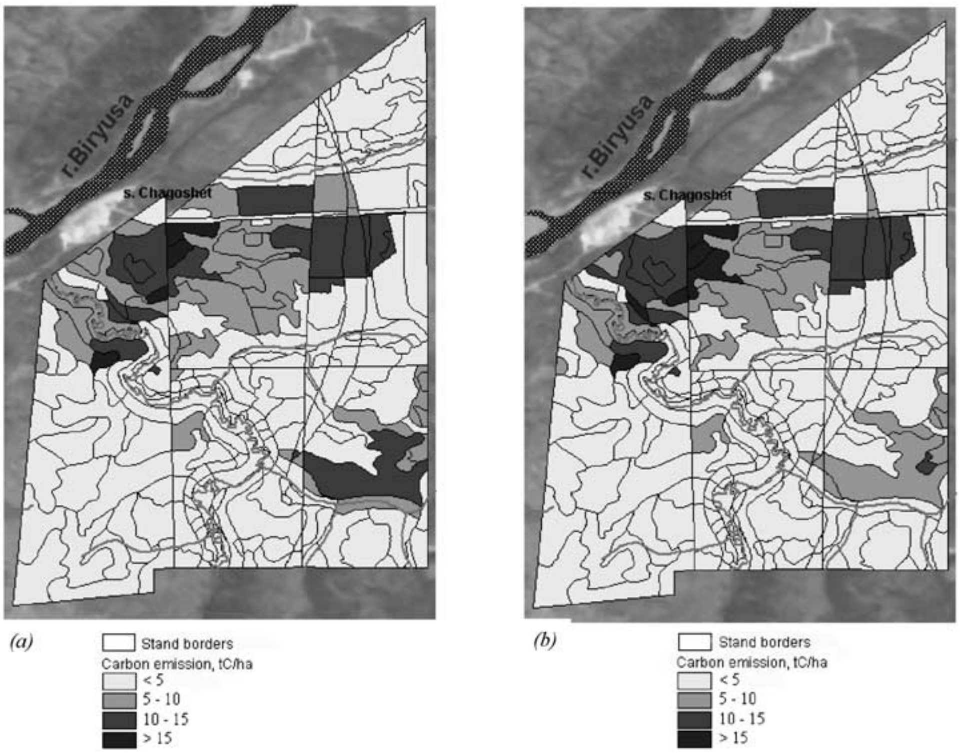


Figure 5. Carbon emissions assessed using (a) aerial photographs and (b) national security data.

Using the large-scale aerial photographs we found that the total mass of fire carbon emissions from the entire burn area of our test site was 16,065.7 tonnes. When we used the data from the national security systems, it was 15,080.9 tonnes. The 6% difference between these numbers shows that the results are highly representative.

6. Conclusion

We developed and tested a method to assess the level of forest fire damage. This method combined data from civilian and national security satellite systems. We developed new algorithms for assessing fire carbon emissions based on remote sensing data and on forest inventory data.

The research showed that our initial theoretical hypotheses were correct. The correlation function that connects NDVI difference from before to after burning with the forest fire damage was linear, and the coefficients of linear correlation were high ($R^2 = 0.82$ and $R^2 = 0.89$). We also found a good agreement between the interpretations of data from national security systems and from aerial photography. When we tested the sample of 35 test plots, the result was a good correlation ($R^2 = 0.8$), which demonstrates rather high correspondence between the forest fire damage parameters as measured by the two approaches. The results show that the methodology developed for the assessment of fire carbon emissions from forest inventory data, satellite images, and sampling large-scale aerial photographs or the data from national security systems has potential. This is supported by the small disagreement (less than 10%) between the fire emissions measured by the two methods.

Our research shows that combining information from national security systems and civilian satellite systems for assessing forest fire damage has a high potential. The data from national security systems can be an advantageous enhancement, and often an alternative to the traditional methods that employ field research and large-scale aerial photography. Forest vegetation parameters measured by national security systems can be used as input parameters in computing post-fire forest carbon emission. The proposed methods can be employed in the development of the national systems that measure human emissions of greenhouse gases, as suggested by the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) [19].

Acknowledgements

We would like to thank F. I. Pleshikov, E. K. Kiseliakhov, V. D. Perevozchikov from the Forest Institute of the Siberian Branch of Russian Academy of Sciences for their input during the field research, and V. M. Skudin and M. V. Dvoriashin from the East-Siberian Forest Inventory Enterprise for providing forest inventory data and aerial photography.

References

1. Artsibashev, E. C.: 1977, *Remote Sensing in Forest Fire Protection*, Leningrad, 27 pp.
2. Baret, F. and Guyot, G.: 1991, 'Potential and Limits of Vegetation Indexes for LAI and APAR Assessment', *Rem. Sens. Env.* **35**, 161–173.
3. Bartalev, S. A., Korovin, G. N., and Shlepak, B. V.: 1977, 'Assessments of Forest Fire Recognition, Using the NOAA AVHRR Radiometers', in *Proceedings of International Forum on Problems in Science, Technology, and Education*, Vol. II, Moscow, pp. 22–25.
4. Conard, S. G. and Ivanova, G. A.: 1988, 'A Differential Approach to Numerical Assessment of Forest Fire Carbon Emissions', *Lesovedenie (Forestry)* **3**, 28–35.
5. Isaev A., Korovin G. et al.: 1995, 'Carbon Stock and Deposition in Phytomass of the Russian Forests', *Water Air Soil Pollut.* **82**, 247–256.
6. Isaev, A. S., Korovin, G. N., Sukhikh, V. I., Titov, S. P., Utkin, A. I., Gulub, A. A., Zamolodtchikov, D. G., and Priazhnikov, A. A.: 1995, *Ecological Problems of Carbon Dioxide Sequestration through Reforestation and Afforestation in Russia*, Analytical Research, Centre of Russian Ecological Policy, Moscow, 155 pp.
7. Janetos, A. and Isaev, A. S. (eds.). *Research of Parameters and Sustainability of Boreal Forests, 1st and 2nd Reports*, U.S.-Russian Joint Commission on Economic and Technological Cooperation. Environmental Working Group. Report Number 291500-1-T. 92-20085, 13 pp.

8. Janetos, A., Shugart, H., Orlick, B., Murphy, T., Kasischke, E., French, N., Stone, T., Isaev, A. S., Sukhikh, V. I., Zhirin, V. M., Bartalev, S. A., Ershov, D. V., Shatalov, A. V., Gurskits, M. N., Pismennii, A. N., Ziemelis, T.A., and Ivanov, S. V.: 1999, Research of Russian and U.S. Alaska Boreal Forests, Using the Images from National Security Systems, Issledovanie zemli iz Kosmosa (Research of the Earth from Space), 6, pp. 83–92.
9. Krankina, O. N. and Dixon, R. K.: 1994, 'Forest Management Options to Conserve and Sequester Terrestrial Carbon in the Russian Federation', *World Resour. Rev.* **6** (1), 88–101.
10. Kurbatsky, N. P.: 1970, *Investigation of Storage and Characteristics of Forest Fuel Materials, Problems of Forest Pyrology*, Institute of Wood and Forest, SO RAS, Krasnoyarsk, pp. 5–59.
11. Kyoto Protocol of UNFCCC.
12. Official Instructions on Forestry Inventory in Russian Forest Fund,. Adopted 12.15.1994 by Rosleskhos, No. 265.
13. Pereira, M. C.: 1999, 'Comparative Evaluation of NOAA/AVHRR Vegetation Indexes for Burned Surface Detection and Mapping', *IEEE Transact. Geosci. Rem. Sens.* **37** (June), 217–226.
14. Perry, C. R. and Lautenschlager, L. F.: 1984, 'Functional Equivalence of Spectral Vegetation Indices', *Rem. Sens. Env.* **14**, 169–182.
15. Recommendations to Forest Fire Detection and Extinguishing: 1977, *Collected Official Documents and Instructions on Forest Fire Protection*, Russian Federal Forest Service, Moscow, pp. 27–113.
16. Shvidenko A., Nilsson S., and Rozhkov, V.: 1994, *Possibilities for Increasing Carbon Sequestration through Improved Protection of Russian Forests*, IIASA, WP-95-86, Laxenburg, 27 pp.
17. Utkin, A. I., Gulbe, T. A. et al.: 1994, *Biological Productivity of Forest Ecosystems. Computer Database*, Institute of Forestry, Russian Academy of Science (RAS), CEPL RAS, Moscow.
18. Utkin, A. I., Zamolodtchikov, D. G. et al.: 1977, 'Measurement of Carbon Storage on Test Plots: Comparison of Allometric and Volume-Conversion Methods', *Lesovedenie (Forestry)* **5**, 51–66.
19. Valendik, E. N., Matveev, P. M., and Sofronov, M. A.: 1979, *Large Forest Fires*, Nauka, Moscow, 198 pp.
20. Zagreev, V. V., Sukhikh, V. I., Shvidenko, A. Z., Gusev, N. N., Moshkalev, A.G.: 1992, *The All-USSR Official Handbook for Forest Inventory*, Kolos, Moscow, 495 pp.

(Received 23 January 2001; in revised form 19 April 2002)