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Assessment of Central Siberia Forest Ecosystems Sustainability to Forest Fires: Academic Research Outcomes

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Abstract

The majority of negative consequences caused by extreme and natural hazards are qualified as weather and climate-related emergency situations. Programs and measures developed to reduce climate risks for economics should be based on scientific background, R&D projects and ongoing monitoring. Fire has always been remained as the main natural factor devastating forest ecosystems and outlining the status and resource potential of boreal forests. Extremely drought – afflicted hot summer and dry cold winter trigger the risks and consequences of forest fires thus affecting wildlife biodiversity and forest ecosystems performance in terms of CO_2 accumulation from the atmosphere. Multifunctional and sustainable forest management in extreme natural conditions should be initiated on reliable (scientifically-proven) evaluation of ecological and resource potential of the forests with economically-effective approach developed to enhance sustainability of ecosystems to fires and insect invasion.

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1. Introduction

Most part of Siberian forests is periodically subjected to fire challenges that may significantly shift carbon balance towards carbon gases emission to the atmosphere (Conard & Ivanova, 1997; Conard et al., 2002). So far it is still unclear how global climate changes may modify the rate and direction of interaction process between ecosystems and atmosphere. In other words, the ecological consequences of global climate change caused by increased carbon and greenhouse gases emissions to the atmosphere of the Earth are required to be evaluated. The solution for this issue is considered to be complicated as there is a lack of the large-scale and long-term monitoring system for greenhouse gases concentration and components in the surface layer of the atmosphere at the continental scale and ecosystems performance within certain climatic changes observed.

At the present moment, the integrity and potential of Siberian forests are constituently revaluated in terms of global markets. By launching and developing forest management system based on complex assessment which unites operational monitoring and applied research approach, it has become possible to maintain ecosystems productivity and minimize negative effects of extreme natural hazards.

Comparative evaluation of current processes occurred in ecosystems with relation to sustainable long-term forest use enables to reveal adaptation mechanisms of certain ecosystems pertaining to natural and anthropogenic disturbances (drought, fires, logging, chemical burns, flooding, ground water level fluctuation, etc.). Application of modern methods of interpretation based on LANDSAT and TERRA satellite images permits to arrange continuous monitoring of the territory. In the meantime, satellite images validation via terrestrial ecosystems' inventory offers additional opportunities to apply and reinforce remote sensing data reliability. This knowledge is required to develop the complex enhancement technology for resource and ecological potential of Central Siberia forests in certain climatic changes conditions observed.

The research relevance is defined by the necessity to remotely and constantly monitor the dynamic status of forest vegetation and detect the unfavourable effects of natural and anthropogenic factors in advance. The research results will build up the basis for updating the forest ecosystems monitoring system thus providing continuous refresh of the cartographic and attributive database on environment status in its statics and dynamics.

2. Objectives, methodology and research design

Our research work is mainly committed to create interactive data base in terms of GIS and apply the contemporary mathematical tools and software in order to establish the dynamic model of ecosystems useful for different types of forests. Forest inventory and evaluation of ecosystems disturbance were examined on 100 km footprint area of ZOTTO (Zotino Tall Tower Observatory) assigned to monitor greenhouse gases in the terrestrial ecosystems of boreal zone of Yeniseysky district of the Krasnoyarsk territory. The tall tower (300 m high metal tower with meteorological and gas detection equipment) was constructed with financial support from International Science and Technology Center (Projects № 2757, 2770) in collaboration with Max Planck Institute for Biogeochemistry (Jena, Germany). It is located close to Zotino village in the Krasnoyarsk territory (Coordinates: 60 N, 90 E).

The footprint of the tall tower covers the left and the right bank of Yenisey-river. The main morphostructure of the left bank is West Siberian Plain (Kasskaya lake alluvial plain and alluvial valley of Yenisey-river). The right one has the following morphostructure: Central Siberian Plateau (Bakhtinskaya depositional plain and right bank terraced Yenisey valley). The landscape was developed mainly by means of multiple water streams of Yenisey-river: Sym, Dubches, Vorogovka, etc. Because of slight territory slope, the rivers are characterized by shaped channels and wide valleys with many oxbow lakes. Developed hydro graphic network, certain uplift of this part of the lowland and wide-spread incoherent outwash specify its bogginess (11% of total area) (Klimchenko et al., 2011).

100 km footprint area of ZOTTO is poorly industrialized. The main type of industrial activity is operational timber processing. The commercial forest exploitation at the researched area has been started since the 70s of the past century and till the present day it preserves extensive features by involving new forest lands. Expansion of felled areas, bared strips for highways and geological exploration sites results in forest territory disturbance. However, the ecosystems of the area researched are mostly damaged by forest fires.

The remote sensing that was held on the basis of the information daily collected from NOAA and TERRA satellites enables to rapidly monitor forest fires. Application of retrospective LANDSAT satellite data provides an opportunity to analyze destructive processes occurred in phytocoenosis (canopy disturbance, fire, felling, windfall) with 30 m spatial resolution. The following research of the fault areas facilitates the qualitative and quantitative description of intensity and consequences of destructive processes.

Siberian forests are always considered to be a hotspot for wild fires. It is influenced by new forest areas exploitation, poor forest conservation lagging behind its standard practical use. Number of forest fires directly depends on people traffic in green zones, tourism development and many other reasons. Dry years that are constantly repeated in the nature from time to time contribute to extremely massive fires outbreaks. The researchers identify not only high natural and anthropogenic fire hazard of the forests but also low forest crop sustainability to fire impact causing its failure in most cases. Methods and algorithm of satellite data processing aimed at assessing territory disturbance qualitatively and quantitatively by means of GIS-technology are specified in the works (Antamoshkina et al., 2008).

At this point, the following basic concepts of ecosystems disturbance evaluation at the tall tower footprint have been generated: the process of data collection and analysis is completed; fire zone evaluation method; fire zone verification algorithm based on full-scale and satellite data of medium and high spatial resolution; fire data base is launched and constantly updated with information obtained from 100 km footprint area of the tall tower and TERRA and NOAA satellites; operational fire monitoring unit in GIS tall tower area with vector layers of fire outlines broken down by monitoring periods is developed and constantly updated.

Another goal of this work is to study tall tower territory disturbance via comparative analysis of forest resources status in the period between 1970 and 2014. Ecosystems disturbance at 100-km footprint area of the tall tower was evaluated by means of archival materials of LANDSAT-series space imagery, topographic maps and fire detection results. Comparative analysis of the disturbance was accomplished in ARC MAP 10.0 software environment by studying vegetation spectral characteristics in terms of Landsat satellite images series and decoding profile of destructive vegetation complex.

Vector-mode results of work (fire shapes, fire site and felling area outlines) were inserted into GIS operational monitoring section with statistic data (numerology required to assess fire sites, burnt and felling areas) uploaded into the operational monitoring base. Results of satellite data processing were validated by field studies held in the tall tower footprint area.

During the studies, research teams inspected different types of ecosystems en route with ocular estimation of forest stands parameters and borders along hiking and water travel directions.

Method of materials collection during surface measurements was developed in collaboration with Max Planck Institute for Biogeochemistry (Schulze et al., 2010; Makhnykina et al., 2013) within the framework of standard practice (Sukachyov & Zonn, 1961).

The network of permanent inventory plots was installed at the transects assigned during field research where the main taxation characteristics, biometric and weight index of forest stands were defined. The sample plots were arranged in classified order. Primary rectangular-shaped transects were lined up to cover the most representative forestland sites of the territory researched. Systematized sample plots layout allows eliminating ultimately any subjectivity influence while choosing location for each sample plot and preserving proportions when selecting correlation of various types of vegetation.

The sample plots were set up actually in the specified areas where the methods of enumeration survey were applied. Consequently, all the parameters of ecosystems were described in details including forest stand taxation characteristics, edaphic conditions and phytocenosis history (origin, fire cycles, anthropogenic impact). Data on ecosystems parameters obtained during the field studies was combined with satellite data processing results and keyed in the database management system Forest (http://forest.sfu-kras.ru).

Difference between some classes outlined at space images and factual types of ecosystems was identified. Adjustments made during route inspection enabled to update the maps of vegetation and ecosystems and also the results of territory disturbance assessment.

3. Discussion of the research outcomes

Fires are considered to be the important natural disaster ultimately affecting the landscape and biodiversity. Attitude towards fires should be based on adequate evaluation of their ecological role. Sustainable development of ecosystems has been evolving for centuries under the influence of forest fires (ranging from light local to crown ones) which play significant role in biogeochemical cycles and carbon cycle in particular.

The climate in Northern territories of the region is distinguished by humidity fluctuation from year to year and frequent dry thunderstorms. Analysis of the fires occurred for the last 5 years revealed that 100 % of the fires had appeared on the territory because of dry thunderstorms. Climate of the district is characterized by harsh continentality. One of the features of the climate continentality is the large amplitude of maximum and minimum fluctuations of air temperature. Low temperatures in winter and high ones in summer are explained by mostly clear anticyclonic weather which causes high cooling of surface air in wintertime and intense heating of it in summertime.

Outbreaks of large and disastrous fires are triggered by weather anomaly such as drought (duration and intensity) and precipitation. Weather anomaly is associated with planet atmospheric circulations which sometimes block up Atlantic cyclones from the anticyclones isolating regions of Russia for a long period of time. Such conditions are considered to be the reason for long-lasting and intense droughts which are likely to generate disastrous fires at times. Fire regime modeling on the boreal forest territory showed that a number of large and disastrous fires had been increased while the inter-fire interval had been greatly reduced respectively.

Analysis of the temperature and precipitation linear trends conducted at Bor meteorological observing station demonstrated that the annual average air temperature amounts to -3.3 degrees Celsius. The annual average precipitation for the same period is 560 mm with positive trend determined. For 72 years of research activities, summer precipitation in Bor-village has been consistent with 199 mm and varied in wide range from 79 (1967) to 338 (1948). In the meantime, there is no tendency for summer values reduction and decrease observed. Winter is appeared to double precipitation from 55 mm to 110 mm per season since 1960.

To accomplish the main objectives stated in the project, we need to define characteristics of typical conditions aimed at developing extreme natural fires in terms of meteorological data and information on current fire hazard situation (Nesterov hydrothermal index, Selyaninov hydrothermal index) (Selyaninov, 1937). Hydrothermal Index (HI) is a nominal parameter describing the moistening level of the territory. Its equation is precipitation sum for the period from t>10°C to evaporation capacity. Evaporation capacity value is nominally calculated as air temperatures sum for the period from t>10°C with 10 times decrease.

Analysis of average HI parameters for the vegetation period did not indicate any remarkable trends shifts but its wide-range variation by years should be noted with dry years (0.5 ≥ HI ≥ 0.7 1938, 1967, 1981 1989) and over moistening years (HI >1.5 1948, 1960, 1987, 1988, 1991 and 2008) clearly tracked. It is reported that in case HI value is about 1.38, the researched area is considered to be satisfactory moisturized with droughts at times and over moistening. Taking into account the peculiarities and square meterage of the territory included into the area of studies, GIS-technology is a key tool to evaluate ecosystems sustainability to forest fires and arrange operational monitoring of territory disturbance. The total square meterage of the territory researched is estimated to be 3 683 139 ha in accordance with the results of comparative analysis on Forest Reserves status (dated from 1970 to 2014), 5 time intervals are selected with the widest disturbance area damaged by felling and slash fire: 1970, 1986, 1999, 2006, 2012. Assessment results are demonstrated running total (Fig. 1).

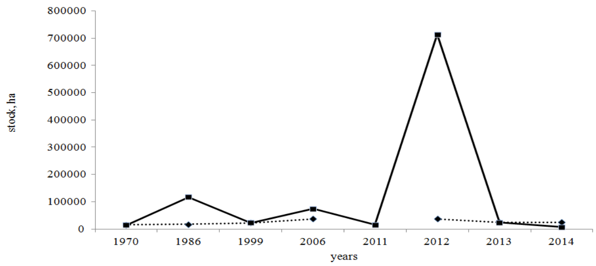


Fig. 1. The chart of territory disturbance within 100 km footprint area of ZOTTO tall tower: 1 – fire zone, 2 – felling area

Previously published articles suggest that fire frequency at the plain landscapes of Yenisei region located in the West Siberian Plain comprises 57 years on average and 70–130 years for dark coniferous forests respectively (Furyaev et al., 2006). As demonstrated by the chart of comparative analysis of territory disturbance covered by footprint area of the ZOTTO tall tower, at the present moment the pyrogenic factor is considered to increase its impact greatly on ecosystems. Regular canopy destruction caused by fires affects age and species composition of stands. The stands research is mainly represented by the final stages of post-fire regeneration with fir forest aged over 130 years and over 160 years related to dwarf pine and spruce forests respectively. The research also shows pine woods as declining stands classified by lichenous and moss types of forest. Therefore, the primary and secondary fire sites are appeared to increase in fire intervals and regenerate normally by long—rated chief species (parvifoliate stands).

However, the forecast for space variation of temperature conditions on the territory of Russia during fire season is determined by the thermal regime cyclicity (Valendik et al., 2014). Knowledge of possible changes in the fire frequency scale requires to further investigate ecosystems adaptation to forest fires. Fire frequency and intervals indicate the status and dynamics of forest canopy that is why their research and regulation should be taken as a basis when facilitating forestry measures and standards.

The picture illustrates that most part of the territory disturbed is affected by fires more than once. As of the current date, the territory disturbance within 100 km footprint area of the tall tower is of about 24.6% of total area researched (Fig. 2). It should be noted that 65% is accounted for old felling and burnt areas. Consequently, the soil surface accumulates half-burnt fuels (stubs, deadwood and windfall) and dry felling residues which easily conduct fire in terms of excessive temperatures.

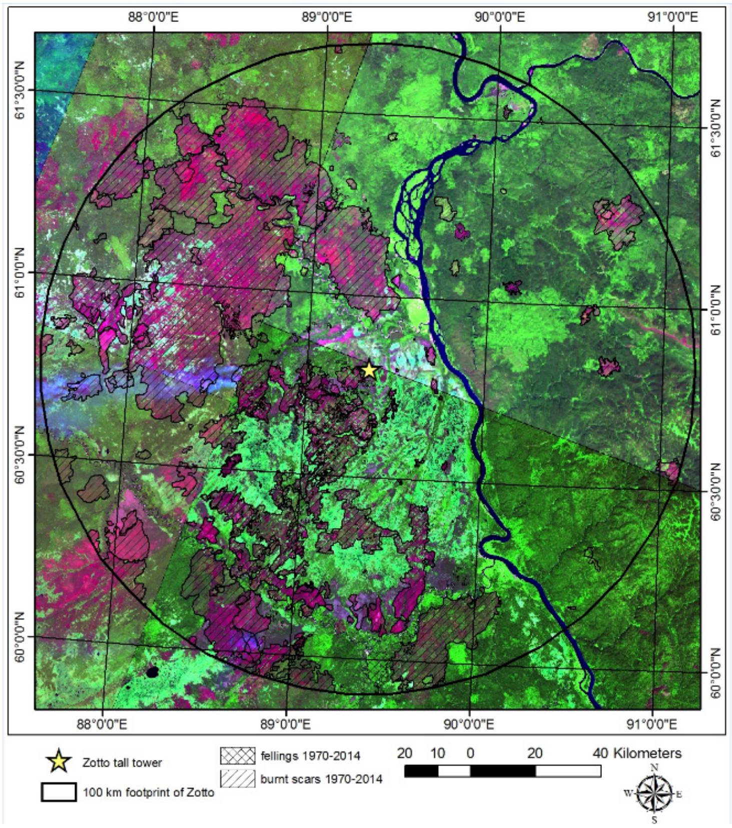


Fig. 2. The territory of 100 km footprint of the tall tower disturbed by fires and felling over the 1970 - 2014 period

The massive forest fires in 2006 and 2012 have contributed a lot to the forest resources structure. It is explained by excessive temperatures in spring-summer period and precipitation deficit ranging from 66 to 88% (Valendik et al., 2014). Droughts and dangerous fires in Siberia relate to the planet atmosphere circulation specified by the anticyclonic trend. The analysis of correlation between fire frequency and meteorological data showed their poor inverse dependence on annual precipitation (R_{june}=-0.354, R_{july}=-0.446) and medium dependence on August temperature (R=-0.650).

Types of land surface. Due to analysis of the satellite data collected on the tall tower footprint area, there are 10 aggregated types of land surface specified (Fig. 2). It has been also established that of about 84% of the area is covered by the forest. Bogs are considered to be on the second place (11%). In 2000, the area of dark coniferous forests (spruce, fir and dwarf-pine woods) comprised 48 % thus dominating among other forest vegetation types. Hardwoods (birch and aspen) accounted for 12% of the area were developed on felling and burned sites. Recent felling and fire areas cover 3 and 5 % of the territory respectively.

In accordance with the data as of 2014, large-scale fires occurred in 2006 and 2012 have led to significant redistribution of land surface areas (Fig. 3). The proportion of fire sites has been increased from 5 to 28% of total researched area and amounted to 890 000 ha with the basic part referred to mixed taiga forest (402 000 ha). The area of lichenous and moss pine forests has been decreased on 1 and 5% with deciduous ones reduced on 2% respectively.

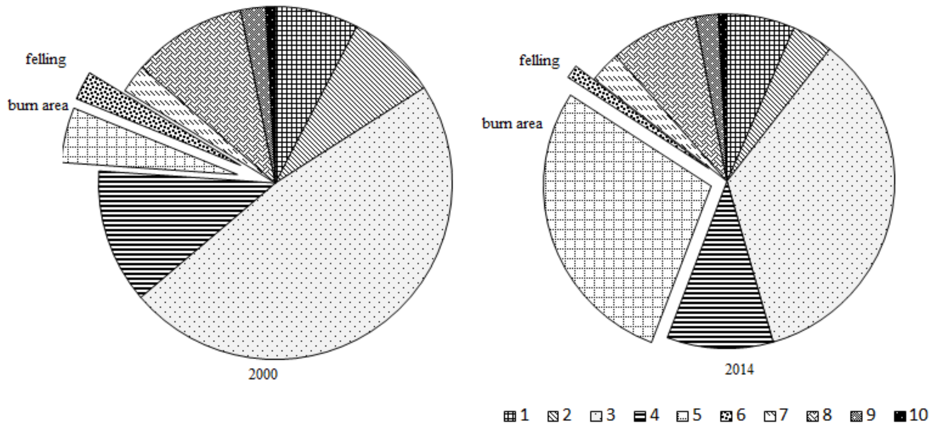
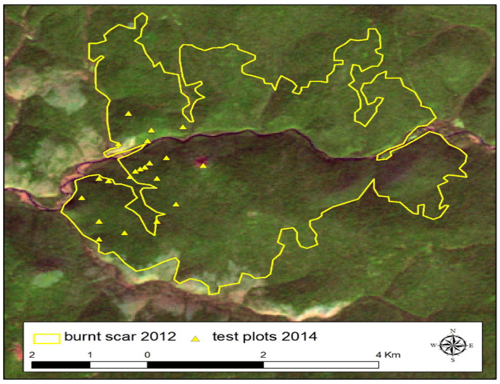


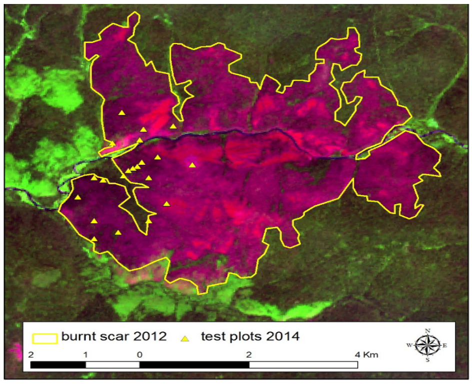
Fig. 3. Dynamics of the land surface area in accordance with LANDSAT space imagery classification (1 – lichenous pine forest, 2 – moss pine forests, 3 – dark coniferous, 4 – deciduous (birch, aspen), 5 – burnt area, 6 – felling, 7 – non-plant areas, 8 – bogs, 9 – water reservoir, 10 – grass and bushes)

The research contains the data on post-fire conditions of forest stands collected during field works held in 2013 and 2014 at the right and the left banks of Yenisei-River in the river basins of Vorogovka, Kutukas and Dubches (Fig. 4 shows the sample plots arrangement at the Kutukas-River). The following satellite data was applied: LANDSAT OLI multi-spectral imagery; information of current fires received through thermal channels of MODIS satellite.

Dark coniferous forests are considered to be of primary concern in terms of long-term fire consequences according to carbon dynamics evaluation. Therefore, the research is specially focused on taiga forest. GIS, ERDAS IMAGINE and ArcMap were facilitated to accomplish the objectives listed. The map chart of vegetation surface types in the researched area was available as it had been preliminary developed by means of satellite images classification results. Based on the map chart, it has been investigated that dark coniferous stands covered more than 90% of pre-burnt area observed. (Fig. 4a).



a)



b)

Fig. 4. Area burnt in 2012 located near Kutukas river: a) Landsat 5, September 13, 2011; b) Landsat 8, August 17, 2013

The boundaries of fire sites were outlined by semi-automatic decoding of Landsat images via region growing technique applicable in GIS ERDAS IMAGINE. The images utilized to extract the boundaries of fire sites were obtained in 2013 and 2014 as soon as fire season was over at the researched territory. Existence of fire activity is confirmed by the information collected through thermally active points of MODIS satellite thermal channels reported by the satellite data receiving and processing station of V.N. Sukachev Institute of Forest SB RAS (Krasnoyarsk, Russia).

The level of fire damage mostly characterized by the ratio of forest crop inventory lost to its total stock before burning was estimated by NDVI (Normalized Difference Vegetation Index). NDVI was specifically calculated for the fire sites researched in accordance with Landsat satellite images. The percent of fire sites loss counted due to field research data was compared to NDVI values at the sample plots locations. Overall, the data for 25 locations was subjected to comparison. The regressional dependence was created in the end as shown in Fig. 5. It illustrates the high level of correlation between NDVI values and the percent of growing stock loss at the fire sites (R^2= 0.802).

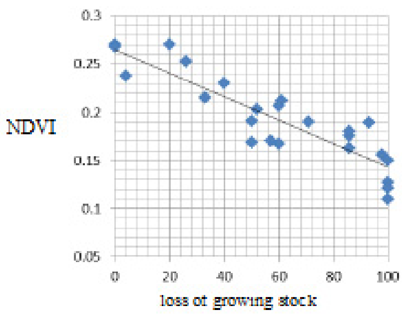


Fig. 5. Correlation between NDVI and percentage of biomass loss at the test plots

There are 5 classes of fire damages identified to visually evaluate the level of post-fire destruction at the burnt areas. The classification is sorted out to the extent that the higher class number shows the lower destruction intensity. Consequently, all the range of values coherent with loss of growing stock at the fire sites observed (percent of the main growing stock loss) was equally divided on 5 groups. The following average loss values were highlighted:

- I class of damage: loss of growing stock 80-100%;
- II class of damage: loss of growing stock 60-80%;
- III class of damage: loss of growing stock 40-60%;

- IV class of damage: loss of growing stock 20-40%;
- V class of damage: loss of growing stock 0-20%.

NDVI values defining different levels of disturbance were obtained in the equation by means of substituting percent regression which had limited each class. Hereafter, all the fire sites were specified by disturbance level based on NDVI values. The classification results were transferred from raster form into vector one where all the classes reviewed were represented as test sites objects. All the test sites were efficiently generalized. Borders of test sites with damage classes inspected were reorganized from rectangular shape typical for pixel image to flattened one typical for natural objects borders. The operation results of the test sites are exemplified in the Fig. 6.

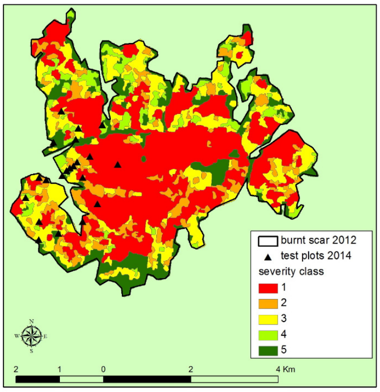


Fig. 6. Classes of post-fire disturbance identified by means of remote sensing data

The footprint of the tall tower is represented by the left and the right bank of Yenisei-River. The main morphostructure of the left bank is West Siberian Plain (Kasskaya lake alluvial plain and alluvial valley of Yenisei-River) with forest stands dominated by lichenous and moss pine woods. The right bank morphostructure is characterized by Central Siberian Plateau (Bakhtinskaya depositional plain and right bank terraced Yenisey valley) with canopy mostly consisted of cedar and spruce woods which are frequently substituted by aspen and birch after fires. Analysis of the data collected at the sample plots network allows assessing the structure of organic matter stocks allocation in forest crop and soil in terms of disturbance frequency occurred (forest fire and felling).

The distribution of organic matter (OM) stocks in the undisturbed dark coniferous stands is shown in Fig. 7 where the average forest crop stock changes with age from 113.9±20.4 to 295.4 m^3/ha reaching its maximum level in mature stands (337.0±19.6 m^3/ha). The stock of coarse woody debris (CWD) at different stages of successional development may greatly exceed the living woods inventory (for middle-aged and declining stands with 1.4 and 2.1 times respectively) with its dynamics of distribution illustrated by U-shaped curve. The balance between the stocks of living woods and CWD reflects the dynamic processes in ecosystems functioning and complies with the concept of global degradation of dark coniferous forests as a whole.

By analyzing fire influence on forest ecosystems sustainability (Fig. 8), it is obvious that the stands affected by forest fires are unable to keep up with undisturbed ones in terms of living wood stock. At the same time, CWD pool notably surpasses phytomass stock so as phytodetritus plays the main role in developing carbon dioxide flows to the atmosphere, these ecosystems will contribute to CO_2 emissions to the atmosphere in the long run.

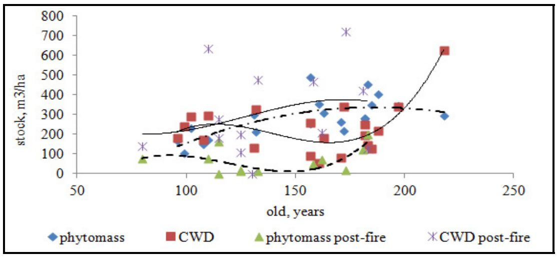


Fig. 7. Dynamics of phytomass and phytodetritus stocks in disturbed and undisturbed dark coniferous forests

Fig. 8 shows that the dynamic balance in ecosystems functioning requires more than 35 years recovering when C atmosphere consumption intensity needed for OM production exceeds or remains in balance with mineralization carbon flow to the atmosphere.

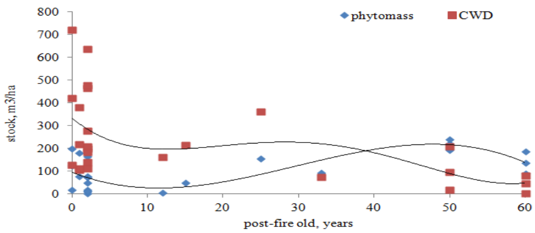


Fig. 8. Dynamics of phytomass and phytodetritus stocks in disturbed and undisturbed dark coniferous forests

The zonal and ecological characteristics of forest ecosystems at the researched area of the left bank part of Yenisei-River are determined by heavy natural fire hazard of pine woods and their phytocoenotic and adaptation features. They are revealed by forest fire frequency, fire distribution and ecological consequences.

Fire frequency and inter-fire intervals are appeared to constantly attribute the development of structure and ecological function of pine stands. Analysis of phytomass and phytodetritus stocks distribution dynamics indicated the typical trend (Fig. 9) as shown by U-shaped curve. As the pine stands are predominantly of pyrogenic origin, the considerable reserves of CWD accumulated in the young forests are explained by its stocks inherited from the forest crop grown earlier. According to global practice, post-fire observations should be arranged at least for 5 years as it is considered to be complicated to detect the strength and the level of fire influence on certain phytocoenosis structures. After the crown scorching and cambium thermal damaging, trees tend to be more vulnerable to repeat disturbances such as forest fires and infestants spread outbreaks. The regeneration rate is markedly affected by repeat disturbances depend on growth conditions and pre-fire type of forest.

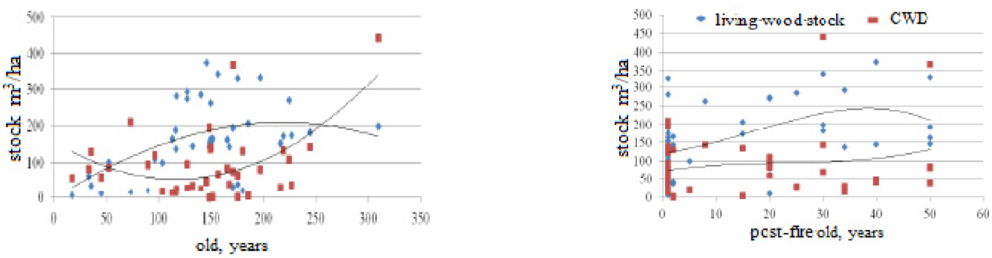


Fig. 9. Dynamics of phytomass and phytodetritus stocks in the pyrogenic pine stands

Analysis of forest regeneration process observed at the burnt areas of different time periods made it clear that the left bank part represented by lichenous and moss pine woods is mostly recovered without species composition succession after burning. The shrub layer is undergrown with pine and mixture of aspen and birch wherein the site condition is reliable to produce economically-valuable pinery in case there are no repeat fire disturbances occurred in the burnt areas. The territory of pine stands suffered by high-intense ground and crown fires (Khariuznaya overflow land) has also been distinguished with regeneration processed through species composition succession (birch, aspen, fir, spruce). The amount of young growth appeared at the large burnt areas of all types of forest after medium and low intensity ground fires is estimated to be not below satisfactory level. Apart from the species composition succession, the level of ground waters is recorded to be greatly modified. To study this issue in details, a number of field experiments have already been arranged with the results available next year.

Forest regeneration of the right bank part of the test site demonstrated that all the recently burnt areas are recovered by derivative birch woods. The quality and quantity of young forests are considered to be satisfactory for birch woods development as well as dark coniferous woods layer (cedar, spruce, fir) will be formed under their crown cover once they are 60 – 80 years old.

4. Conclusion

Completed studies are committed to advance methods of presenting, processing and analyzing spatial information on forest territory status exemplified by measurements collected at 100-km footprint area of the tall tower (Zotino – village, Krasnoyarsk territory). Furthermore, the parameters research results pertaining to the most representational types of ecosystems and their variability were obtained to be supposedly applied for CO_2 fluxes modelling and calculation at the footprint area of the tall tower. These fluxes would be compared to the ones measured via in-situ methods at the tall tower.

Fires make the greatest contribution to changes in the carbon cycle with direct influence lasting of about 40 years (low-intensity fires in pine stands) and up to 300 years (high-intensity crown fire).

Non-significant (1%) impact of timber processing sites on ecosystems disturbance in Yenisei-Siberian district is detected and reviewed. The pyrogenic factor is tracked to be greatly increased as well as the burnt areas are expected to be extended with forest regenerated via long-term dominant species succession.

The methods of operational monitoring represented and annually arranged in accordance with actual satellite data enable to adjust the functional role of forest ecosystems in case of disturbance (felling, fire). The applied archival satellite data allowed to track forest disturbance dynamics caused by fires and felling for more than 40-years period originally at the territory researched. The geoinformation system was established based on the results of the ecosystems disturbance assessment. It applies cartographic, reference and operational data as a unique information resource capable to manage, develop orders and visualize cartographic materials. Information integrated through different resources of GIS environment provides broad options for spatial analysis.

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