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A remote sensing based approach to determine forest fire cycle: case study of the Yenisei Ridge dark taiga

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ABSTRACT

The role of fire disturbances in boreal regions is of great importance for the global carbon cycle, but for the boreal forests characterized by a low fire frequency (i.e. the dark taiga of Siberia) it is often difficult to identify the fire cycle and the fire disturbance rate. A new methodological approach, based on remote sensing techniques and homogeneous stochastic process properties, has been developed for quantifying the forest-fire cycle. In the following study we selected a forest area, the Yenisei Ridge dark taiga, in central Siberia where field and satellite imagery data were collected, and where this new methodology was applied. For the central Siberian dark taiga, the fire cycle was estimate to be 520 yr.

1. Introduction

Forest fire has been identified as important natural disturbance factor in boreal forests (Goldammer and Furyaev, 1996). These fires occur as stand-replacing fires, which initiate a new succession of vegetation or cohort of trees, or as ground fires, which affect the population structure (Wirth et al., 1999). Ground fires occur in fire-tolerant stands of pine (*Pinus* spp.) or larch (*Larix* spp.), and their frequency can easily be studied from tree ring analysis. In contrast, in Siberia stand-replacing fires are the main event that start a new succession in fir (*Abies* spp.) stands (Kurbatsky, 1962) which provide ladder fuels for fire to reach the crown (Furyaev, 1983). It is only young stands of pine and larch that are prone to crown fires, because they often have not self-pruned and their branches extend all the way to the ground, providing ladder fuels for any fire that should occur. While pine and larch develop even-aged cohorts of trees after fire, the situation can be more complex in *Abies* forests of North America and of Siberia (West et al., 1981), because post-fire succession begins with both conifers and broadleaved species such as birch (*Betula* spp.) and aspen (*Populus* spp.). However, the broadleaved trees grow faster and dominate the vegetation in the first century after a fire. Conifers will eventually overgrow these deciduous trees and then form a boreal forest that is characterized by a mix of evergreen and deciduous trees. Finally, this mixed boreal forest will be almost totally replaced by conifers which can be killed by wind disturbances and insect infestation. It is impossible for this conifer forest to return to the deciduous forest stage without fire. For this forest type, with a low fire frequency and for which the fire cycle overpasses the medium life age of the tree living in the forest, it often remains a very difficult problem to identify the fire frequency (Furyaev, 1983), because no dead trees that are killed by fire remain as long as the total fire cycle.

The role of fire disturbances in boreal regions is of great importance for modelling the carbon exchange of a boreal forest (Bergeron et al., 1998). To our

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knowledge, at present the mean fire cycle in the Yenisei Ridge dark taiga is unknown. In the following study we will present a new approach, based on remote sensing, by which the mean time for crown fire recurrence can be quantified.

Furthermore in calculating the potential terrestrial carbon uptake of the Eurasia region, forest fires need to be included together with estimates of productivity by models or direct measurements. The balance between carbon uptake and release through fires is eventually a small number (Buchmann and Schulze, 1999) as result of the difference of two relatively large fluxes (net ecosystem uptake and fires). A preliminary estimation of net biome productivity will also be derived from the fire cycle determination.

2. Theory

The forest-fire cycle is defined as the time period required for an area equal to the entire area of interest to burn in its entirety (Canadian Committee on Forest Fire Management, 1987). The study of the forest fire cycle in this new methodological approach is based upon a multi-temporal spatial assessment of burnt areas and upon a multiscale analysis of the spatial pattern distribution of these burnt areas.

The main hypothesis of this research is that the annual probability of fire in any point of the whole forest ecosystem is reflected in the area cover fraction and in the transitory time of the first stage of the forest secondary succession after a fire event under the following two conditions: (1) the first secondary succession stage must have an almost null probability of burning during its transitory time; (2) the forest area is only affected by homogeneous stochastic fire events. To satisfy the stochastic conditions the following spatial–temporal assumptions must be verified (Johnson and Van Wagner, 1985; Johnson and Gutsell, 1994): (1) each element of the study area must have on average a constant fire regime during the time-span of the study; (2) collectively the elements of the study area must all have the same fire regime.

The two assumptions can be met if the study follows these criteria: (1) the time period covered by the study is long enough so that the periodicity of particularly severe or light fire years is small compared with period of study; (2) the study area is vast enough to encompass repeatedly the largest fires that naturally occur in this region.

The formula definition of our main hypothesis is that the annual probability of fire in any forest point, p, can be estimated as simple ratio of the first-stage area fraction to its average transitory time:

$$p = \frac{\text{first-stage area fraction}}{\text{first-stage average transitory time}}.$$

p is also the fraction of the whole forest that burns every year (Van Wagner, 1978). The reciprocal of p is then the fire cycle C, i.e. the number of years required to burn over a forest area equal to the whole study area.

$$C = 1/p.$$

As the first stage of the forest secondary succession is the direct result of fire events, a remote sensing image could be used as a historical database that represents the cumulative spatial distribution of all fires which occurred during the first stage transitory time. In fact, remote sensing images can be used to determine the spatial area fraction of the first secondary succession stage.

Furthermore, with a remote sensing temporal dataset which covers a time period that is within the temporal statistical boundary conditions, it is possible without ancillary ground data to determine the first stage transitory time. In fact the transitory-stage time is equal to the reciprocal of the average annual change rate of the stage area fraction.

The transitory-stage time could be related to one or all the early post-fire forest succession stages (recently burnt area, grass/forbs, shrubs/seedlings, sapling/pole, mature) until these are well detectable in the remote sensing images. The first transitory stage (time since fire) is longer and is possible to use as referent study period, and the collection of a suitable statistical fire event database is easier. If the available remote sensing dataset does not cover a suitable time-span study, it is necessary to use field data in compliment to determine the transitory stage time.

As satellite earth observation images can cover large areas, it allows the spatial statistical conditions to be easily satisfied. Moreover the use of very large homogeneous areas permit to reduce the constraints of the temporal statistical conditions.

3. Area of study

The study area (Fig. 1) is located in central Siberia on the eastern side of Yenisei River between the tributary rivers Angarà and Podkamennaya Tunguska, with

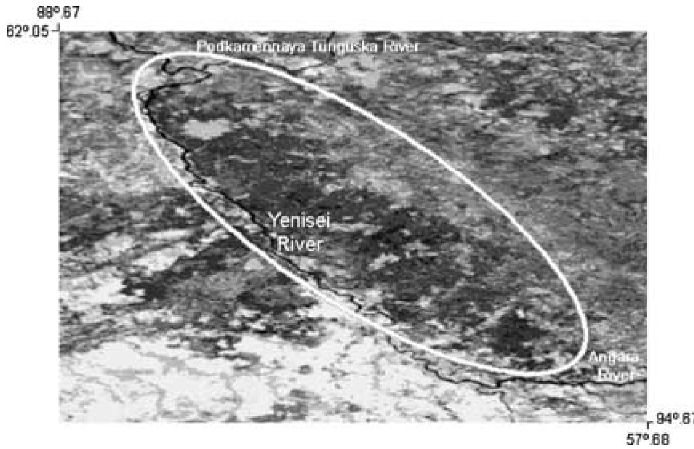

Fig. 1. Summer mosaic image of the study area from the VEGETATION-SPOT4 satellite. The dark tones inside the white line represent the Yenisei Ridge dark taiga area. The image has been georeferenced to geographic (Lat/Long) projection (WGS 84 datum).

a latitude range from 58°.00 to 62°.00 N and a longitude range from 89°.60 to 94°.00 E. The whole area has homogeneous environmental characteristics and uniform climatic parameters: 600–900 mm as average annual precipitation; −24 °C as an average minimum winter temperature; and 16 °C as an average maximum summer temperature.

In this area the last stage of the secondary forest succession is an old growth coniferous taiga mainly composed of the following species: *Abies siberica, Picea obovata, Pinus sibirica, Populus tremula, Betula pendula*. The total area extension is 4.51 million ha and represents the Yenisei Ridge dark taiga territory (Kalashnikov, 1994).

In the Yenisei Ridge dark taiga, the broadleaved birch dominant canopy represents the first forest secondary successional stage after a stand-replacing fire disturbance (Furyaev, 1983; Razumovsky, 1981, 1999; Scherbina, 1999, 2000), but this canopy, unlike the coniferous dominant canopy, can not support any crown fire (Van Wagner, 1983). The area percentage of all kinds of dark taiga in Russia is around 13% of all forest (Svidenko and Goldammer, 2001), and generally fires in these high-rainfall forest ecosystems are very rare, with up to 200–300 or more years of fire recurrence, but damage is very severe (Svidenko and Goldammer, 2001). In this forest area, active fire fights were never applied by the Forest Fire Service. Forest fire events were only monitored through airplane or helicopter recognitions.

Forest fires are mainly generated by lightning. In a recent study on Siberian forest fires (Ivanov, 2000), lightning is reported to account for more than 60% of the ignition sources in the dark taiga, while another 30% are unknown and 5–10% are due to human activities.

Man has never really colonized this zone, as human activities are limited to a few mining settlements in the southern part of the zone. The area is used by a few hunters and isolated people who are generally not a source of anthropogenic fires, because they use the forest as a food and income source. In this region, human forest disturbance has probably been larger only during the intensive geological exploration period, 1960–1975.

This forest area represents one of the largest remaining pristine boreal forest areas of the world.

4. Materials and methods

4.1. *Description of satellite remote sensing and field data*

A set of different satellite remote sensing data were used: (1) coarse spatial resolution (1 km) SPOT VGT S-10 products (10-d composites) covering the full year 1999 over the full study area; (2) fine spatial resolution (30 m) LANDSAT ETM+ recorded on 11 July 2000 covering part of the study area. The coarse spatial resolution data covering the full study area were used at the regional scale, spatial resolution >100 ha, while the fine spatial resolution image was used on a landscape scale, minimum spatial element resolution

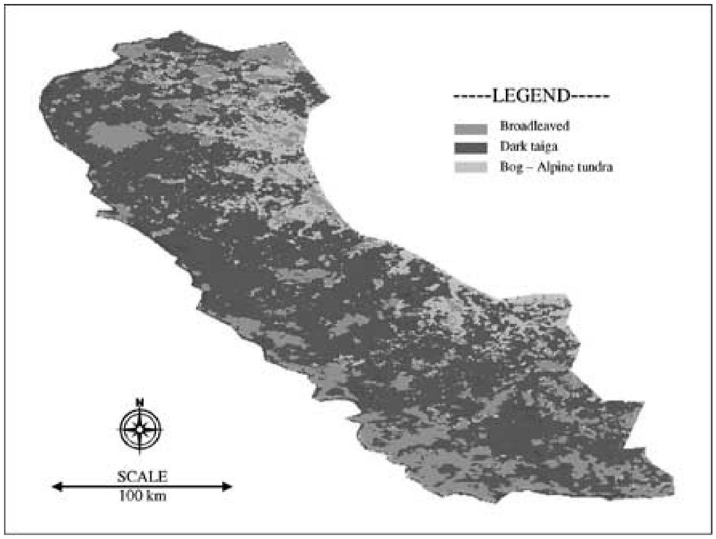

Fig. 2. Broadleaved–coniferous area supervised classification of the Yenisei Ridge dark taiga, (derived from the VEGETATION-SPOT4 mosaic image).

>0.5 ha (Forman and Godron, 1986), for a detailed analysis. A summer mosaic image created from the multi-temporal SPOT VGT data (Bartalev et al., 2000) was used. This mosaic is cloud-free and keeps most of the spectral information of the single 10-d composite products. Forest floristic composition data and woody cores were collected during three field expeditions in the summer of year 1999 and the spring and summer of year 2000. The field data were used as training and validation input to support the remote sensing analysis.

4.2. *Description of methods*

Four methodological steps were applied on the satellite imagery: (1) A digital supervised classification of the SPOT-VGT mosaic image was produced using the field training areas. The resulting map (Fig. 2) was used to assess the area extensions of the different forest types in the study area. (2) A spectral analysis of the different classified forest types was carried out in order to evaluate the accuracy of the resulting classification and derived area estimations. (3) On a subset of the study area covering 800 000 ha, a spatial landscape analysis, using a supervised classification of the Landsat ETM+ image, has been performed to study the historical crown fire behavior. (4) The classification derived from the SPOT VGT mosaic image (Fig. 2) has been used to analyze the fire event frequency and to study the recurrence of exceptional fire events (Fig. 3).

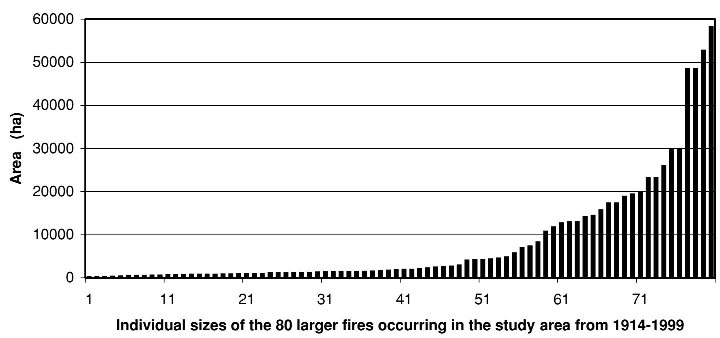

Fig. 3. Area extension of the 80 larger fires occurring in the study area from 1914–1999 (referent study span period).

5. Results

In this study, the first-stage area fraction was estimated from the remote sensing dataset. Because a suitable temporal remote-sensing dataset was not available for the transitory stage time, field data have been used to determine this parameter. As the birch-dominant canopy is the last fire stage that does not burn during its stage transitory time and that is detectable in the remote sensing image, the area fraction and transitory stage time of the birch-dominant canopy were studied. So within the area fraction and in the transitory stage time are also included the area and transitory time of the early successional stages, i.e. the non-closed canopy area and period. In this study case the sampling time period is equal to the time period necessary to obtain a coniferous dominant canopy after a fire event.

5.1. Ground data analysis

During the field campaigns, the main measured parameters were the age and composition of the forest stands. Particular attention was given to young stands with recent fire activity (i.e. fire scars, dead trees, etc.). During the field explorations in the study area, forest succession stages or large coniferous forest areas without *Abies sibirica* trees were never found. This is an important indicator that most of the fires are stand-replacing in that area, because surface or ground fire usually kill the fir trees. This tree is a very fire-sensitive species (Furyaev, 1983). It is possible to find few and small forest areas ($<$0.5 ha) without fir trees. These areas are generated by lighting on the ground when the environment and weather conditions are not favourable for forest fire ignition.

After a destructive forest crown fire the territory is recolonized by birch trees (*Betula pendula*) and aspen trees (*Populus tremula*). Although most of the tree species which compose the mature forest stand, are already present in the first 50 yr after the fire, the birch trees generate a uniform dominant or sub-dominant canopy layer. This layer will remain until the birch trees are affected by strong intra- and inter-specific competition for resources. The homogeneous birch-dominant canopy constitutes the first stage of the *Abies*-dominated taiga. This birch canopy is the only one identified as broadleaved forest in the remote sensing classification result.

More than 100 woody cores in many different young forest stands and six 10×100 m floristic transects were collected to estimate the birch canopy medium transitory time (Table 1).

The aspen-dominant layer is not always present. When present it is not uniform and has a clumped spatial distribution. The birch canopy transitory stage time depends mainly on the intensity of the fire event. Surviving coniferous trees are able to generate an earlier competition effect through seed supply. Generally the birch canopy transitory time varies between 80 and 90 yr. In this study 85 yr duration will be used as the average transitory time, which includes the transitory stage time of the non-closed initial canopy. This period (85 yr) also represents the average time that is necessary to obtain a coniferous dominant canopy after a stand-fire disturbance, and it is also equal to the time since fire.

5.2. Area extension assessment

The ground test areas were first utilised in order to compute the statistical distance between spectral signatures of the different forest canopy types from various satellite remote-sensing images. As the spectral properties of the broadleaved trees are different from the coniferous trees (Fourty and Baret, 1998) the

Table 1. *Characteristics of the early secondary succession stages*

	Dominant canopy layer			
	Birch (shrubs)	Birch	Aspen	Fir
Not dominant canopy	–	*Abies sibirica, Pinus sibirica*	*Abies sibirica, Picea obovata, Pinus sibirica*	*Abies sibirica, Picea obovata, Pinus sibirica*
Maximum age, yr	15	90	180	230
Transitory stage time, yr	1–15	15–90	50–180	100–230
Canopy cover, %	0–90	70–95	20–40	60–90

birch-dominant canopy, which is the only broadleaved dominant secondary succession stage, can always be easily separated from all the other forest canopy types.

Using the result of this initial analysis a digital supervised classification (maximum likehood probability) of the whole study area was made (Fig. 2), and an analysis of the spatial pattern distribution of the broadleaved canopy forests was carried out. As any fire event is identified as a continuous single broadleaved pattern, an underestimate of the number of fire events and also an overestimate of the single fire-event areas is possible in the case of area-connected fire events, but that will not affect the total burnt-area fraction.

The classification of the study area provides the following results: 16.3% of the whole forest area is covered by canopies that are dominated by broadleaved trees and by areas that are occupied by an initial non-closed canopy after fire; these canopies were generated during the last 85 yr by more than 150 single-fire events, and 80 of these have an extension greater than 200 ha (Fig. 3); in these last 85 yr the study area was affected by four exceptionally large fire events (about 50 000 ha each).

5.3. Verification of the conditions of the theory

The forest-fire behavior was studied through a spatial analysis (derived from remote sensing) of the burnt areas supported by ground-based data. One result is that particularly intense fire events are not controlled or limited by any territorial characteristics such as topography (the presence of hills or slopes) or hydrology (the presence of rivers). For example, in 1960 near the Sulomay settlement an intense fire forest event initiated on the north side of the Podkamennaya Tunguska River crossed the river at a point where the river is more than 400 m wide. This result demonstrates that with respect to forest fire our study area is geographically continuous, as there are no territory characteristics that control the fire spread. Moreover, in contrast to the region on the west side of the Yenisei River, the study area does not contain extended areas of bogs that could stop canopy fires.

In our study area it is only the weather conditions (lightning, precipitation, wind, etc.), which fully control the fire spread (Johnson, 1992). Thus, from the remote-sensing point of view our study area fits the initial theoretical conditions. Indeed the study area is vast enough (4.5 million ha) to encompass repeatedly the large fires that naturally occur in this region (50 000 ha), and collectively all the forest area has the same fire regime.

During our study time-span in the Yenisei Ridge dark taiga many different fire events had happened (more than 150, including 80 large and four exceptional). Thus our study area also verifies the initial condition from the temporal, i.e. the study time period is long enough compared to the periodicity of particularly severe or light fire years.

5.4. Fire cycle determination

In order to determine the fire probability we calculate first the annual area that is burnt as fraction of total area, p, from the fraction that is occupied by broadleaved canopy and initial non-closed canopy after fire (0.163) and the average birch canopy stage transitory time (85 yr) using the simple ratio:

$$p = \frac{\text{birch canopy area fraction}}{\text{birch canopy transitory stage time}} = \frac{0.163}{85} = 0.0019$$

The mean fire cycle, C, is then:

$$C = \frac{1}{0.0019} = 377 \text{ yr.}$$

A simple analysis of the sensitivity of the fire-cycle determination method was made. If the largest fire event (58 000 ha) is not taken into account, the fire-cycle period will change from 520 to 556 yr (i.e. a variation of 7%). This shows that the method is quite robust.

6. Discussion

The *Abies*-dominated forests represent a considerable proportion of the northern circumpolar region, but, because of low fire frequency, little fire research has been conducted until very recently (Furyaev, 1983). This paper is trying partly to close this gap in knowledge. The study was focussed on the determination of two main parameters: the average transitory time of the birch canopy and the relative extension of this canopy layer. These parameters, area fraction and transitory stage time, are easy to determine from two different methodological approaches, remote sensing and dendrochronology, with good confidence.

The resulting fire cycle for the Yenisei Ridge dark taiga, 520 yr, is much longer than literature values, 50–200 yr (Goldammer and Furyaev, 1996; Svidenko and Goldammer, 2001). Furthermore, this reported fire recurrence (520 yr) is a conservative estimate, because it includes natural and anthropogenic fires averaged over the past 85 yr. It is possible that the fraction of anthropogenic fires has increased in the past 50 yr, which would mean that the present-day fire cycle is shorter. Previous studies utilized data at a stand-level scale, in particular collecting fire-scar series, where the fire disturbance effects are more complex. In fact at this level it is possible that a fire generated from lighting occurs on a small area extension (less then 0.5 ha) as a surface fire. In this case the forest fire is not a stand-replacing fire, and the first succession stage is not the birch canopy. From the ground analysis we realized that a significant disturbance generated by surface fires does not exist in the dark taiga. Due to the multilayer canopies and due to dry twigs and branches that are not shed in *Abies* and *Picea*, fires always develop into crown fires. Fire scars are rare, and are found on trees that have survived crown fires. Thus the fire cycle is different from that found in Siberian pine or larch forest (Sannikov and Goldammer, 1996).

Understanding and quantifying the role of forest fires on the carbon budget of regions is not an easy task; particularly large uncertainties are associated with the proportion of burned biomasss, the decay of wood after fire and the role of charcoal. However, the problem of NBP estimates of Russian regions is becoming particularly relevant, especially in the framework of the Kyoto Protocol negotiations (UNFCCC, 2001). To this purpose and with the aim of providing a preliminary assessment of the role of forest fires in the Siberian region, we use the IPCC guideline methodologies on Land Use Change and Forestry (IPCC, 1997) to estimate carbon losses through forest fires. The IPCC guidelines are not well developed for such complex problems, since they consider a land-use change associated with fire that is not always true for a natural forest, where a regeneration cycle follows a fire event. However, the methodologies of the IPCC guidelines can provide, especially in our case of study where only forest stand replacing fires are taken in account, a first estimate of the average carbon emission associated with the fire.

Under these assumptions it is possible to derive a preliminary assessment of the carbon losses by fire for this region (net biome productivity) based on newly available data, such as net ecosystem carbon exchange data (Röser et al., 2002) derived from a mosaic of successional stages of such a biome. Taking an average annual estimation of 227 g C m^{-2} for the dark taiga carbon ecosystem exchange, the total Yenisei Ridge dark taiga, 4.5×10^6 ha, would assimilate 10.2×10^6 t C yr^{-1}(NEP, net ecosystem productivity). In our estimate of mean fire recurrence, every year about 0.19% of the total land is subjected to burning. During a crown fire event the fire fuel load immediately is only a part of the forest biomass (Van Wagner, 1983), but the forest dies (except for few trees) and the dead trees decay over a period of about 50 yr (Schulze, 1999). Considering a mean above-ground biomass of 125 t C ha^{-1} (author's direct measurements; Adams, 1998) the total carbon released, as an aggregate of the immediate and decay carbon emission (IPCC, 1997), from the annual burned area is 1.07×10^6 t C yr^{-1}. The annual losses by fire decrease the NEP by about 10.4% (long-term average). Thus the pristine Yenisei Ridge dark taiga, which is an unmanaged forest in terms of wood extraction, has an annual mean carbon budget of 9.13×10^6 t C yr^{-1} (NBP, net biome productivity). This is still a high estimate, because it does not include other disturbances which are not included in the NEP measurement, such as wind break and death by insects. However, this estimate demonstrates the importance of fires for the carbon cycle even in habitats that are generally wet.

Nevertheless, this estimate is only preliminary, but clearly shows the importance of considering disturbances in the carbon cycle assessment and the need for further regional studies to investigate in more detail this delicate balance.

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