4.2 MEAN FIRE RETURN INTERVALS AS INDICATORS OF CHANGE IN BOREAL SIBERIA

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1. Introduction

Boreal regions are particularly significant because these are the regions that are predicted to experience some of the largest temperature increases from climate change. Atmosphere Ocean General Circulation Models are in agreement that boreal zones may experience temperature increases of up to 40% greater than the global mean (IPCC, 2001), and increases of 2-3^{o}C have already been observed over the past three decades (Balling, R. C., Michaels, P. J., and Knappenberger, P. C., 1998). Additionally, the largest reservoir of terrestrial carbon resides in boreal regions, which could be released with increased fire and feedback to the atmosphere (Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., Simpson, L. G., and Vinson, T. S., 1993: Zoltai, S. C. and Martikainen, P. J., 1996).

Boreal forest communities are particularly responsive to climate change, which is evident when examining historic fire regimes (Clark, J. S., 1988), current fire-induced forest-tundra fragmentation (Payette, S. and Gagnon, R., 1985: Sirois, L., 1992), as well as twentieth century area burned trends (Flannigan, M. D. and Harington, J. B., 1988: Stocks, B. J. and Street, R. B., 1982). Under current climate change scenarios, ignitions from lightening, fire season length and fire weather severity are expected to increase, particularly in boreal Siberia. Wildfire acts as a disturbing agent that defines the beginning and end of successional processes that maintain the current stability, diversity and mosaic structure of boreal ecosystems.

With evidence of increased temperatures, one expects evidence of increased fire frequency and area burned. However, an accurate ground-based fire database does not exist for boreal Russia, particularly in the remote northern reaches of Siberia. Forty percent of the Russian forest fund area is not currently and has never received any fire protection or monitoring (Dixon, R. K. and Krankina, O. N., 1993: Sofronov, M. A., Volokitina, A. V., and Schvidenko, A. Z., 1998), and fire records were purposely falsified before 1988 (Shvidenko, A. Z. and Nilsson, S., 2000).

Fortunately, remotely sensed data are capable of discerning fire. The Advanced Very High Resolution Radiometer (AVHRR), aboard U.S. National Oceanic and Atmospheric Administration’s (NOAA) Polar Orbiting Environmental Satellite (POES) series, has shown its ability to detect active fire and identify burn scars (Cahoon, D. R., Jr., Stocks, B. J., Levine, J. S., Cofer, W. R., and Pierson, J. M., 1994: Justice, C. O., Kendall, J. D., Dowty, P. R., and Scholes, R. J., 1996). An AVHRR-based area burned product provides the basis for this investigation

In this study, evidence of fire-induced, climate-related change is investigated in boreal Siberia by comparing calculated mean fire return intervals with published estimates of mean fire return intervals. Because temperatures have already increased across Siberia in the last decades, it follows that the interval

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between fire occurrences should decrease, resulting in a forest mosaic that is younger and more deciduous.

2. Methods

AVHRR-based data are used to estimate area burned, which is overlaid on an ecosystem map to calculate area burned in 58 ecosystems across Siberia. Area burned data from 1995 through 2002 are used to calculate mean fire return intervals for each ecosystem in each year, as well as an average boreal forest fire return interval.

The area burned product is composed of two satellite-derived sub-products, active-fire detection and mapped burn scars. Active fire is detected daily during the fire season at the Sukachev Institute of Forestry in Krasnojarsk, Siberia. Active-fire detection is limited by satellite overpass and cloud cover, which is greater than 60% during the fire season in Siberia. Large fire events are selectively underestimated with active-fire detection (Flannigan, M. D. and Vonder Haar, T. H., 1986: Pereira, A. C., Jr., Setzer, A. W., and dos Santos, J. R., 1991). Therefore, burn scars are mapped in regions with over 50 active-fire detections in a 2-day period. The area burned product is a combination of the mapped burn scars and active-fire detections that lie outside of the scar boundaries.

Fire cycle (Van Wagner, C. E., 1978) or fire rotation (Heinselman, M. L., 1973) is the average time required to burn an area equivalent to the size of the area under study. This does not mean that every region in the study area must burn, just the size of an area equal to the region under consideration. Mean Fire Return Interval (MFRI) is defined as the average time required to burn an area equivalent to an entire ecosystem. Thus, MFRI is defined as:

$$MFRI = \sum_{i=1}^{n} \frac{(I_i A_i)}{A_t}$$

where I_i is the fire return interval of the stand *i*, A_i is the area of the stand *i*, A_t is the total area of the ecosystem, and *n* is the number of even-aged stands in the ecosystem.

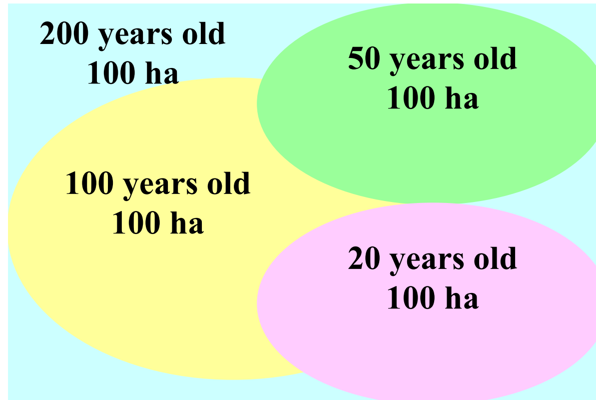

Figure 1. Mean Fire Return Interval (MRFI). The four even-aged cohorts, shown above, range in time since last fire event from 20 to 200 years.

For example, the landscape pictured in figure 1 contains four even aged cohorts, which range in time since last fire event from 20 to 200 years, and the MFRI is 93 years as shown.

$$(200yr)\left(\frac{1}{4}\right)+(100yr)\left(\frac{1}{4}\right)+(50yr)\left(\frac{1}{4}\right)+(20yr)\left(\frac{1}{4}\right)=93yr$$

If a landscape had an average MFRI of 100 years, it would be expected that an average of 1/100 (0.01) of that landscape would burn annually. Using satellite-derived data, the total area burned in an ecosystem is divided by the total area of that ecosystem, resulting in the fraction of area burned in a specific ecosystem for each year (i.e. 0.01 = 1/100 or MFRI = 100 years). Under this fire regime, if young forests are defined as ≤ 20 years, then 20% of the forest would be young forest (0.01*20).

3. Results and discussion

Fire varies widely, both temporally and spatially, as well as annually and interannually. Of the 58 ecosystems analyzed, 16 ecosystems experienced greater than 0.5 million hectares (M ha) burned in a single year. To put that in perspective, in some years only 1.0 M ha burns throughout the entire country. Wetlands (bogs and floodlands) and the raised Central Taiga consistently recorded a large amount of area burned. One reason for this is these are extensive ecosystems than span throughout Siberia.

Comparisons between literature-based published estimates of MFRI (reported) and those calculated in this investigation are shown in table 1. Under a warmer scenario, fire is expected to increase, resulting in a decrease in MFRI, the average time required to burn an area equal to the area of the ecosystem. The calculated MFRI for boreal forests is less than the reported MFRI, as expected. The calculated mean and range are within the range of the reported MFRI.

Light Coniferous Forests also reveal a decreased calculated MFRI when compared with the reported mean, and the mean is also within the range of reported MFRI. Additionally, Floodlands (Bogs) show a decreased calculated MFRI and the calculated mean is just below the reported range of MFRI.

Both the Central Taiga calculated MFRI estimates are greater than the reported MFRI. The calculated raised Central Taiga estimate is within the range of the reported means, and the low-lying calculated mean is slightly greater than the reported range. One reason for the larger calculated means is low intensity surface fires are typical of both of these ecosystems, and surface fires could be selectively underestimated by the AVHRR because surface fire intensity is low, the fires are relatively brief, and the canopy cover is undamaged by surface fire events, obstructing the satellite's view.

In the Central Taiga case, the published estimates are based on extensive field-based studies. The low-lying Central Taiga of Western Siberia was studied for 20 years and fire history data is available back through 1700. Fire scars from numerous tree-ring cross-sections were analyzed to construct chronologies in the raised Central Taiga, also providing data back through 1700. Even though these investigations provide exceptional long-term MFRI, the spatial scales analyzed are small in comparison to the area of the entire ecosystem (figures 2 and 3). The study area analyzed in the low-lying Central Taiga is 165,000 ha (1,650 km^2), and the area analyzed in the raised Central Taiga study is about 57,000 ha (570 km^2). In comparison, the area of the ecosystems are extensive, resulting is large numbers in the denominators and lower MFRI.

Additionally, the reported MFRI are long-term and are subject to varying historic climate-related differences in MFRI. Over a 256 year period, 533% of the 165,000 ha low-lying Central Taiga burned, which results in a MFRI of 48 years. From 1700 to 1793, the MFRI was 769 years; over 5-year periods in both 1870 and 1915, 85% of the area burned, resulting in a 4 year MFRI; and more recently, from 1931 to 1952, the MFRI was 33 years. It is not unusual for fire regimes to vary, even in the short term. For example, based on 20 years of statistical fire data from 1980 through 1999, the largest area burned annually is 21 times greater than the smallest area burned annually in Canada and 12 times greater in Russia (Johnson, T., 1999: Johnson, T., 2001: Shvidenko, A. and Goldammer, J. G., 2001).

Even though the calculated and reported MFRI differ spatially and temporally in both the raised and low-lying Central Taiga, the MFRI are remarkable similar, highlighting the viability of satellite-based MFRI as a method to access potential climate-related change.

The Dark Coniferous Forest and Forest Tundra calculated MFRI are both greater than the reported MFRI, but again both are within the range of the reported MFRI. Northern and Sparse Forest ecosystems are the one exception, in that the calculated MFRI is much greater than the reported MFRI and the reported range of MFRI.

Not surprisingly, regions with the smallest MFRI are located in the southern reaches of Siberia, where most of the fire events occur. These regions are also far less extensive than the Central Taiga ecosystems. Figure 4 shows the ecosystems with the smallest MFRI, Central Asia Montane Steppe, Central and Southern Taiga (low-lying), and Far East Moist Broad-leaf (low-lying).

Based on forest inventory data, Shvidenko and colleagues (1998) estimate that young stands make up about 7% of the coniferous forest forming species and

6% of deciduous forest forming species are young stands. If young stands are ≤ 15 years and 13% (half non-forest burned) of the area is in young stands, then the MFRI is 115 years. This value is well within the range of calculated boreal MFRI (61 to 227 years) and shows that the percentage of young forest stands can be estimated with satellite data. This provides further evidence of the viability of satellite-derived MFRI as a method to monitor change in boreal forest.

4. Conclusions

With the exception of one ecosystem, all of the calculated MFRI are within or very close to the range of the reported MFRI, which means that the method is feasible. The MFRI calculated in this investigation provide baseline values from which future spatial and temporal comparisons of fire-induced land cover change can be compared. To our knowledge, this is the first attempt to calculate remote sensing-based estimates of MFRI for greater Siberia. Because fire data for Siberia is scarce and because this is a region that is sensitive to expected climate-induced change, this method could be a useful tool when accessing potential change in the remote and vast boreal Siberia.

More than half of the calculated MFRI are greater than the reported MFRI, which was not expected. Under current warmer conditions, area burned and fire frequency are expected to increase in Siberia, but a decrease in MFRI is not detected in this analysis. Without longer-term complete fire records, this is difficult to access. Differences in the spatial and temporal resolution of the data could have factored into the discrepancies. However, the overall boreal forest MFRI is less than the reported MFRI, which is consistent with an increase in fire.

This research demonstrates that remotely sensed data can be used to define MFRI in boreal Siberia, however improvements in the accuracy of MFRI would result from improved accounting of area burned. Additionally, because the amount of area burned in boreal regions is highly variable, a long-term, consistent fire database would also result in more accurate estimates of MFRI and allow for long-term comparisons of potential changes in MFRI in individual ecosystems. The AVHRR instrument has been collecting data since 1979 and would be useful in compiling a long-term, consistent fire database, which could be paired with contemporary instruments (MODIS) to identify and monitor potential fire-induced change from 1979 into the future.

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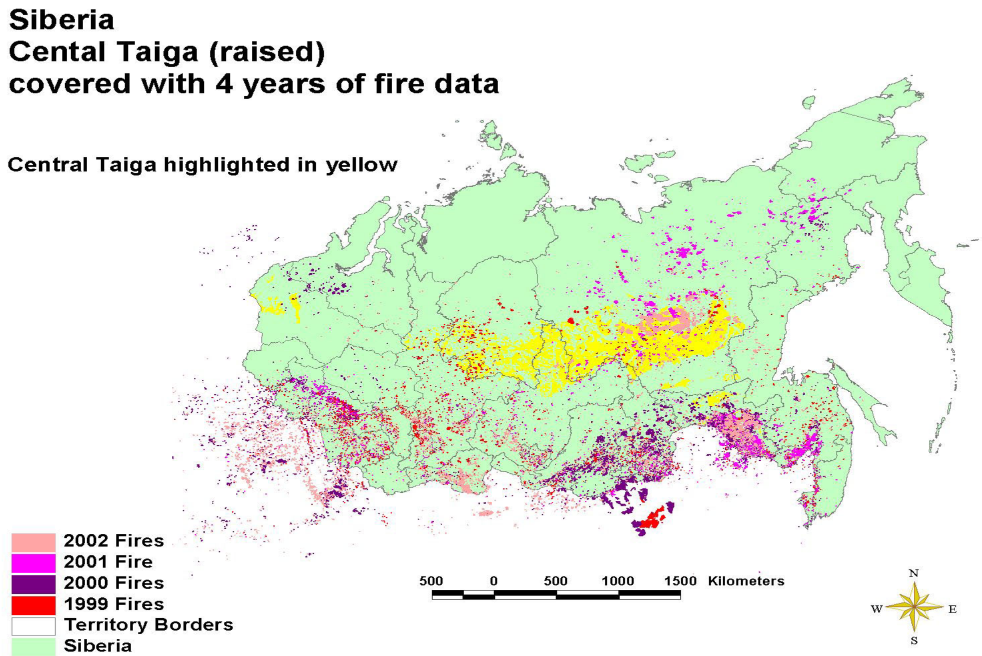

Figure 2. The raised Central Taiga is highlighted on a map of Siberia along with the location of fires mapped from 1999 - 2002. The majority of this ecosystem lies at northern latitudes (~ 58 to 64^{o}N) and spans thousands of kilometers. Fires primarily occur at lower latitudes (~ 45 to 57^{o}N).

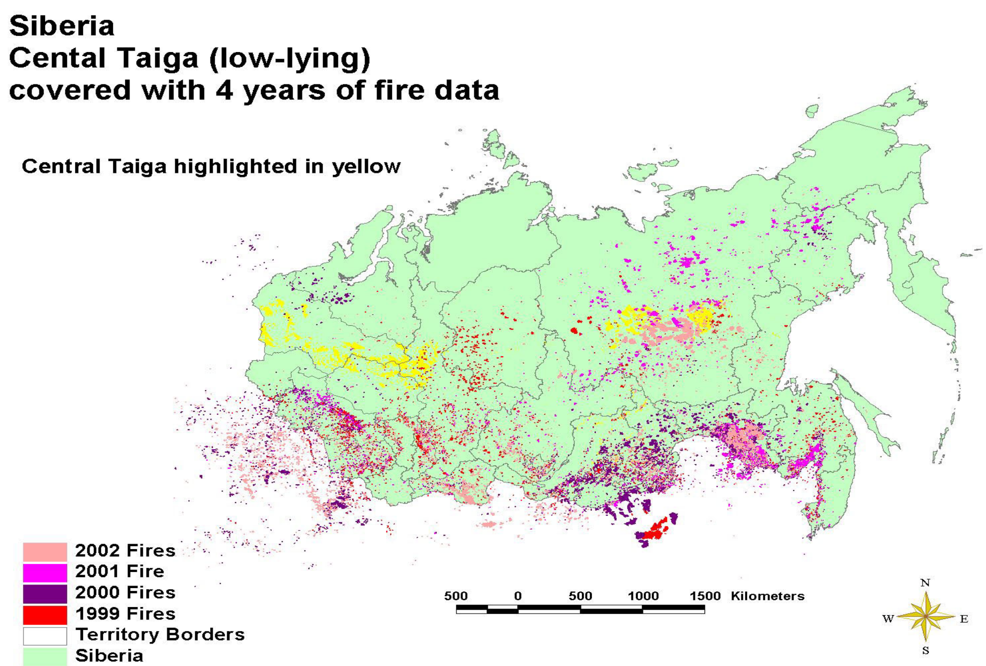

Figure 3. The low-lying Central Taiga is highlighted on a map of Siberia along with the location of fires mapped from 1999 - 2002. The majority of this ecosystem lies at northern latitudes (~ 58 to 64^{o}N) and spans thousands of kilometers. Fires primarily occur at lower latitudes (~ 45 to 57^{o}N).

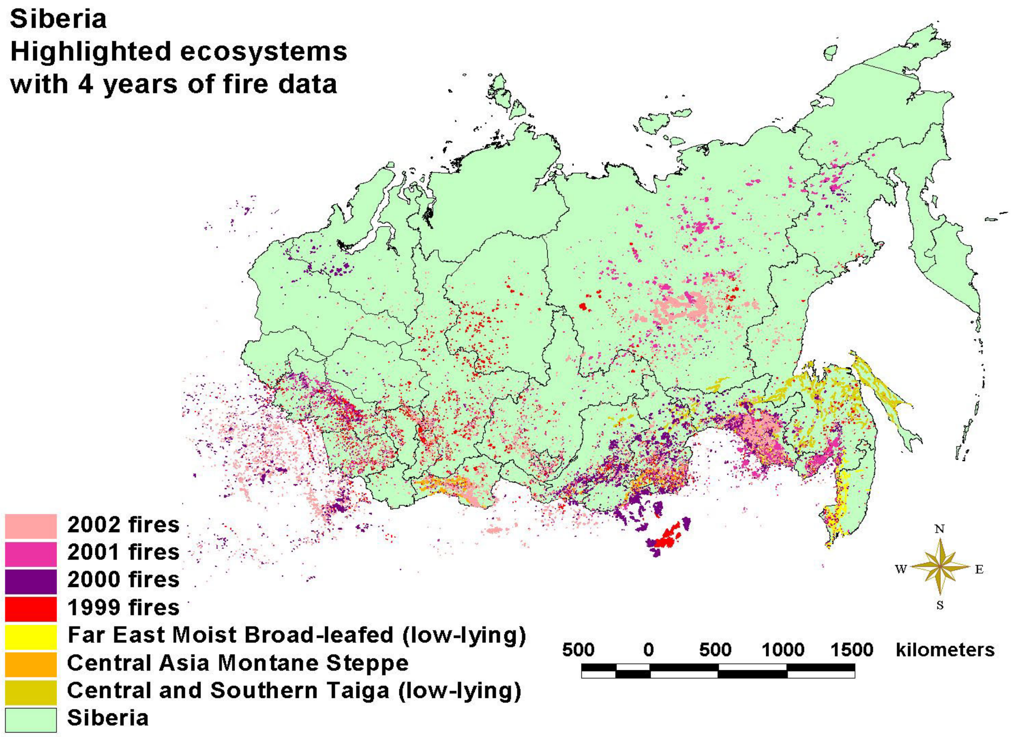

Figure 4. The location of ecosystems with the smallest Mean Fire Return Intervals (< 26 years) are shown along with fire locations mapped from 1999 - 2002. The majority of these ecosystems are located at lower latitudes where fire primarily occurs.

Table 1. Comparison of calculated and reported Mean Fire Return Intervals. *Values are italicized when the calculated MFRI is less than the reported MFRI.*

Ecosystem (number of values in calculation) [number of values in literature]	AVHRR-based Mean Fire Return Interval (range) Years	Dendrochonolgy-based Mean Fire Return Interval (range reported) Years
Boreal Forest *(7) [6]*	*90* *(61 – 227)*	*139* *(50 – 270)*
Central Taiga (low-lying) Kos-Yenisey Plains (7) [1]	132 (58 – 323)	48 (18 – 130)
Central Taiga (raised) Yakutia (7) [1]	76 (26 – 333)	35 (6 – 77)
Light Coniferous Forest *(7) [4]*	*36* *(17 – 133)*	*41* *(15 – 70)*
Sphagnum Pine and Peat Forest *(7) [6]*	*69* *(44 – 250)*	*192* *(70 – 300)*
Northern and Sparse Forest (29) [2]	357 (227 – 556)	90 (80 – 100)
Dark Coniferous Forest (33) [5]	196 (75 – 725)	128 (70 – 200)
Forest – Tundra (17) [N. America - 2]	1111 (330 – 52,631)	815 (180 – 1450)

Reported sources

Boreal: Heinselman (1978); Zackrisson (1977); Shugart et al. (1991)

Central Taiga (low-lying): Antonovski et al. (1992), from Furyaev and Kireev (1979)

Central Taiga (raised): Ivanova (1996)

Light Coniferous Forest: Shvidenko and Nilsson (2000)

Sphagnum Pine and Peat Forest: Shvidenko and Nilsson (2000)

Northern and Sparse Forest: Shvidenko and Nilsson (2000)

Dark Coniferous Forest: Shvidenko and Nilsson (2000); Furyaev (1996)

Forest – Tundra: Payette et al. (1989)