The frequency of forest fires in Scots pine stands of Tuva, Russia

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Abstract
Forest fires resulting from long periods of drought cause extensive forest ecosystem destruction and can impact on the carbon balance and air quality and feed back to the climate system, regionally and globally. Past fire frequency is reconstructed for Tuvan Scots pine stands using dendrochronology and statistics. Central Tuvan Scots pine (Pinus sylvestris) stands are subject to annual fire regimes; however high intensity fires are rare but they are responsible for most of the damage. Low, medium, and high severity fires have shaped the multi-story Scots pine communities, locally and regionally. Fire type and frequency are directly related to weather and climate and are also dependent on anthropogenic influences. The primary dry period, which promotes fire ignition and spread, in Tuva occurs in April and May. In some years, the precipitation deficit combined with high air temperatures induces long periods of drought. Unlike the typical surface fire regime, forest fires that burn during these extreme droughts often become crown fires that result in substantial forest damage and carbon release. The mean fire interval (MFI) is found to be 10.4 years in Balgazyn stands, and the landscape-scale MFI is 22.4 years. High severity, stand-replacing crown fires have a longer MFI. The warmer and dryer weather that is predicted by global climate models is evident in Tuva, and we believe that these changes in weather and climate have resulted in increased fire intensity and severity, rather than fire frequency in the Tuvan region.

Keywords: dendrochronology, forest fires, Scots pine (Pinus sylvestris), Tuva, Siberia, Russia

1. Introduction
Forest fire is a key ecological factor controlling forest development (Furyaev 1996). Fires burn frequently in Scots pine stands that are widely distributed across Siberia (up to 30% of all conifer stands). Mean global air temperature has increased by 0.74 °C (range 0.56–0.92 °C) from 1906 to 2005, and temperatures are predicted to increase by 1.8–4 °C (range 1.1–6.4 °C) by 2090, depending on the Intergovernmental Panel on Climate Change scenario (IPCC 2007). Expected changes in climate are predicted to result in considerable increases in fire intensity and area burned, with a simultaneous reduction in mean fire return intervals (Stocks et al 1998, Furyaev et al 2001, Kasischke and Turetsky 2006, Krawchuk et al 2009). Changes in fire regimes, under the influence of weather and climate, will influence the ability of seedlings to regenerate and force change in species distribution by migration, substitution or extinction (Weber and Flannigan 1997). Fire acts as a catalyst for that change, and ultimately ecosystems will be transformed into different ecosystems that are in balance with the contemporary climate (Soja et al 2007). Current observed changes in climate have already induced vegetation zone movement, and substantial decreases in tundra areas and an expansion of steppe and desert ecosystems are predicted (Tchebakova et al 2005, Soja et al 2007, Kharuk et al 2007).
Increasing anthropogenic influences and specific weather conditions combined with the existing forest disturbance are responsible for increased forest and steppe fire frequency and vast areas burned in Siberia. The situation is aggravated by the changing climate in southern Siberia, which is evident in increasing winter and summer air temperatures and decreasing precipitation (by 4–8%) (Tchebakova and Parfenova 2006). In fact, observed temperature increases in the region have already exceeded 2090 climate change scenarios (Soja et al. 2007). Forest regeneration on large burned sites found in the narrow-banded southern Siberian Scots pine stands is hampered by the proliferation of grasses (primarily Calamagrostis species) and soil dehydration, and as a result, these sites are gradually being transformed to steppe ecosystems. Fire-caused stand thinning and colonization of trees by pine fungus (Fomitopsis annosa) and insects leads to increasing fire danger in these stands (Buryak et al. 2007). The Tuva Republic is one of the areas in southern Siberia that is characterized by high fire danger.

Detailed forest fire chronology (dating) is a tool that is used to quantify fire regimes, because it provides estimates of fire intervals and frequency. Past forest fire reconstruction enables insights into the multi-century history of forest fire regimes, which can be useful for comparing past and current fire regimes and predicting forest ecosystem development.

2. The study area

Our study is conducted in the Republic of Tuva, which is situated in south-central Siberia, central Asia. Tuva is 169 thousand square kilometers in area and is situated between 49°44′–53°43′ north latitude and 88°52′–99°8′ east longitude. Tuva is a typical mountainous country, with mountain chains crossing it east–westward. Inter-mountain hollows consist of steppe or desert ecosystems. Large mountain ‘knots’ (massifs) are found only in the west and east. Elevation above sea level ranges from 520 to 3976 m. Highly dissected relief, and variations in slope, aspect, and elevation are all factors that interact to yield variability in Tuvan microclimates, soils, and vegetation.

The regional climate is extremely continental and is characterized by cold, dry winters and hot, dry summers with a large range in daily and seasonal temperatures. Prevailing western and northwestern air masses interact with the mountain range to often block atmospheric moisture, which results in irregular patterns of precipitation. For this reason, the Tuvan mountain hollows receive from 186 (Usbnur hollow) to 243 mm (Ulug-Khem hollow) of precipitation. Along with typical inter-annual variations, precipitation distribution is seasonally non-uniform. Most precipitation (up to 70% of its total annual amount) occurs, mainly as heavy showers, in July and August; winter, spring, early summer, and fall are relatively dry.

Dry steppe and semi-desert covers 30% of the Tuvan region, and the remaining 70% (11 390.6 thousand ha) is forested. Highly valuable conifers make up 90.9% of the total forest area; softwood deciduous and shrubs account for 3.4 and 5.7%, respectively. These are primarily larch and Siberian pine stands (90%). Dominant larch forests are found at low and middle altitudes. Siberian pine begins to occur in the forest canopy at 1200–1300 m, and its contribution increases with elevation. Big river flood plains are occupied by mixed stands consisting of aspen, birch, larch, spruce, Siberian pine, and fir. Apart from the Scots pine stands found in Tojin hollow, eastern Tuva, the largest Scots pine stands are located in Balgazyn in the Ulug-Khem hollow, at the southern boundary of Scots pine (Koropachinsky and Fedorovsky 1969), in the central steppe portion of the Tuvan Republic.

3. Methods

Fire activity is analyzed for central Siberia using fire dates and area burned values provided by the Krasnoyarsk Forest Protection Airbase. Fire periodicity and mean fire intervals (MFI) are estimated on the basis of dendrochronological analyses. Scots pines are selected for generating the chronological series and fire reconstruction because these conifers have a long life cycle, are rot resistant, fire tolerant and have distinct tree rings with well-pronounced late and early wood.

Tree fire scar samples (full cross-section tree slabs), taken from the Balgazyn forest, are used to determine forest fire dates on the basis of Madany et al. (1982) dendrochronological methodology that involves cross-dating fires found in the living-tree slabs with those recorded by the slabs taken from tree stumps (Baisan and Swetnam 1990, Swetnam 1996, Swetnam and Baisan 2003). Accordingly, the fire years identified on each of the slabs are then combined into a general fire chronology. Using this fire chronology, we determine temporal variability characteristics, such as the regional MFI and fire periodicity. MFI is calculated as a ratio between the duration of the fire series obtained for the study site to the number of fires recorded over this period of time (Arbatskaya and Vaganov 1997). Five to ten tree slabs are taken at each sample point (maximum distance 10 km) and used to build fire scar-based forest fire chronologies. Because of tree rot, not all of the samples proved useful.

4. Forest fires and fire regimes

Fire ignition and spread in Tuvan forests depend on stand location, climatic conditions, vegetation characteristics, and land use. In the territory of Tuva, forest fires occur annually; however most burning is associated with hot, dry, low relative humidity periods. These factors account for high weather-related fire danger. Dry periods primarily occur in April and May and can persist for longer than 30 days; these months are typically the period of maximum fire activity (53% of all fires) (figure 1). The fire season duration is typically 120–200 days, from the end of April through early September and sometimes expanding into October during exceptionally dry years.

The 1974–2007 dynamics of fire occurrence and area burned is shown in figure 2. Tuva forests are subject to more than 7000 fires, with the greatest number of fires (573) and area burned (209.5 thousand ha) recorded in 2002. The amount of area burned has increased since 1990, and the
Figure 1. Monthly wildfire occurrence in Tuvan forest from 1987 to 2007.

Figure 2. Annual wildfire occurrence and area burned in Tuva forest.

The largest eight reported annual areas burned are all recorded since 1990. The primary wildfire ignition source is human (51% due to carelessness; 31% lightning; and 11% agricultural burning). Arson is also a problem, with the goal of obtaining cheap wood and antlers for trade. The antlers are often made into handicrafts and sold. Additionally, since 1990, the fire and growing season lengths have increased due to changes in weather and climate (Soja et al. 2007). Also, since the collapse of the Soviet Union in 1989, the Aviallesoolkrana (Russian fire fighting organization) has not been well funded, and social, economic and political pressures could have also influenced the consistency of fire recording (i.e. decreased collective farming, limited funds for fire record keeping but less motivation to under-report area burned) (Shvidenko and Nilsso 2000, Soja et al. 2004a, 2004b). Consequently, the reasons for the increases in fire regimes are confounding.

Favorable burning conditions occur annually in the mountain forests of Tuva. In the spring, about 60% of all fire ignitions occur on southern-facing slopes, whereas forest stands found on northern-facing and eastern-facing slopes remain relatively moist and unburned. For this reason, mountain forest fires, unlike fires on the plains, are local, typically only burning one slope. Spring fires are generally surface fires that spread along watershed ridges and burn convex slopes, leaving wet depressions intact. When a fire spreads upslope, it becomes a crown fire and typically results in 100% tree mortality (figure 3). Fires can spread over vast areas disregarding topography after long droughts in late spring and fall.

Forest fire periodicity is influenced by alternating dry and wet years, seasonal and daily weather, temporal changes of vegetation, location of forest stands, and human activity
Figure 3. Burned area in the Tuvan mountains.

Figure 4. Balgazyn Scots pine forest after the 2008 fires.

(Polushkin 1980, Sverlova and Kostyrina 1985, Vaganov et al 1996). Reconstruction of past forest fires on the basis of fire scar analysis for Scots pine stands with lichen ground vegetation of the Tuvan Republic and southern Krasnoyarsk reveal that the fire interval ranged over 2 to 34 years (MFI of 6–11 years). Importantly, these stands have experienced heavy anthropogenic stresses (visiting of forests by local population for the purpose of herb and mushroom picking, wood harvesting, recreation). The MFI is 60–70 years for mixed mountain larch and Siberian pine stands. The late 19th and early 20th century was the highest fire frequency period in Scots pine forests in southern Siberia, with the following exceptional fire years: 1858, 1866, 1901, 1909, 1927, 1934, 1950, 1953, 1981 and 1990 (Valendik et al 1993, Valendik 1996). Several of these fire years overlap with this investigation.

Surface fires of varying intensity are dominant in forest–steppe Scots pine stands. However, crown fires are possible in Scots pine stands, particularly under severe droughts and strong winds. Fire danger is also increased due to multi-story stand structure (ladder fuels). For example, the Scots pine subspecies Pinus silvestris L. subsp. kulundensis Sukaczew found in Tuva is characterized by low tree crowns (Pravdin 1964).

Balgazyn Scots pine stands are underlain by high sand dunes, low sand hills, and plains (figure 4). This uneven-aged pure Scots pine forest with larch as a minor component is supported by shallow chernozem (black earth) mixed with loamy sand and light-gray deep loamy sand. The subcanopy woody species include Caragana arborescens, Lonicera altaica, Rosa acicularis and the dominant ground covers are Carex pediformis, Veronica incana, Potentilla acaulis, Iris ruthenica, Artemisia frigida, and Galium verum.

Fire chronologies are reconstructed in Balgazyn by sampling at three Scots pine locations (figure 5). The tree ring data reveal 25 fires (1760, 1768, 1789, 1805, 1815, 1837, 1846, 1858, 1866, 1873, 1885, 1889, 1893, 1901, 1908, 1912, 1916, 1926, 1939, 1943, 1953, 1967, 1983, 1990, and 1999) over 260 years, between 1747 and 2008. Although fires occur in this stand every year, the MFI for this site type is calculated to be 10.4 years. There are a smaller number of fire scars found in tree slabs since the 1940s due to the annexing of Tuva by the Soviet Union in 1944 and the formation of forest fire protection departments. The implementation of a fire suppression policy soon resulted in a decreased number of fires. To estimate a landscape-scale mean fire return interval, we consider only the fires that persist across the landscape or the fires that leave scars in the same years (synchronous fire dates) on many trees. All these trees are found to record eight fires (4–14 fires) resulting in MFI values of 22.6 ± 2.3 years. Scots pines are a fire-tolerant species and will generally survive low to medium severity surface fires; however severe crown fires will initialize the successional process.

The 1908 and 1926 fires are recorded in most of the sample trees. This suggests that these are years with expansive fires that could have resulted in the occurrence of new tree generations. Some fires are recorded by a small number of trees, which represents small localized fires. Evidence of four summer fires (1866, 1901, 1908, and 1926) is observed in trees at all tree sampling locations, which represents large fires that burned approximately every 20 years. This fire periodicity appears to be constant for the entire recording period, because Balgazyn Scots pine stands have always existed in close proximity to human settlements, while in central Siberian boreal forests, found far away from people, fire frequency increased considerably over the past centuries due to developing of new lands (Valendik and Ivanova 1996). Tuvan Scots pine communities are similar to those found in Mongolia, where the MFI ranges from 9 to 22 years and agricultural fires are one of the main reasons for wildfire occurrence (Valendik et al 1998).

Illegal logging acts to increase fire danger in forest–steppe Scots pine stands. Logging waste, left by illegal harvesters, increases fuel and enhances the potential for high intensity surface fires, which often become forest-destroying crown fires. An area equivalent to the total area of Balgazyn Scots pine forest has been disturbed by fire since 1975 (figures 4 and 6). According to the 1988 State Forest Fund records, Scots pine covered over 20.2 thousand ha of the Balgazyn Forest Management area, and in 2008, the record reports only
Figure 5. Fire chronology for Balgazyn Scots pine forest. The horizontal lines are the sampled life spans of trees, and the vertical tick marks are dated fire scars.

Figure 6. Annual wildfire occurrence and area burned in Balgazyn Scots pine forests, which are located in the Republic of Tuva.

6000 ha remaining (<30%). This analysis shows that since the mid-1990s, the number of fires and area burned in Balgazyn increased by 17 and >60 times, respectively (figure 6). This situation is attributed to decreasing forest fire protection in Tuva due to economics and increasing drought length due to climate change. High to moderate intensity surface fires result in the death of 50–87% of the trees. Post-fire forest regeneration is inhibited because of soil overheating, eroding soil, absence of Scots pine self-seeding, and, in some sites, proliferation of tall grasses, mostly Calamagrostis species. Conversely, Buryak et al. (2007) noted that in some regions vegetation is converted from Scots pine to birch and aspen in microdepressions of regenerating burned sites, and these species serve to shade the ground and, thereby, reduce soil
Fire has a significant influence on the carbon balance (Harden et al. 2000, Amiro 2001, Magnani et al. 2007), with the level of influence depending on the fire severity. In an attempt to roughly estimate the fire contribution to the Balgazyn carbon balance, we calculate the contributions of fires of varying severity on the basis of biomass and area burned on an annual basis (figure 7). Only carbon released from burning of ground fuel is quantified. On the basis of experimental biomass burning data (McRae et al. 2006), low and high severity fires are assumed to completely consume litter, grass, and the low loading moss layers present in the study site, plus 10% and 75% of the forest floor organic matter, respectively. The resulting estimate of potential annual carbon emissions from fire in the Balgazyn stand is 208–415 Mt depending on the fire severity.

5. Conclusions

The warmer and dryer climate characteristics that currently typify southern Siberia are responsible for high fire frequency and large areas burned in this region. Area burned has increased over the past few decades, largely due to climate change; however there are several confounding variables (e.g., decreased funding for the forest service). These forests have consistently been in close proximity to humans, so this is less of a factor for recent increases in fire regimes. The Balgazyn forests are located at the southern border of the steppe and forest–steppe ecosystems, where the initial signs of climate-induced change are expected, and these forests have decreased in area by 70% in the last 20 years.

High fire severity results in increasing carbon loss, which in time, can be offset through the gradual regeneration of the burned sites. While the MFI for Tuvan steppe Scots pine stands is 10.4 years, large fires burn every 22.4 years. According to the dendrochronological analysis, the fire periodicity has not changed in the Balgazyn Scots pine stands over the past three hundred years, because this stand has constantly experienced anthropogenic stresses, even though fire severity and area burned have increased. Large portions of the forest are being converted to steppe ecosystems following fire events, which further inhibits post-fire forest regeneration and could be considered an initial indicator of climate-induced ecosystem change.

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