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The effect of climate anomalies and human ignition factor on wildfires in Russian boreal forests

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Over the last few years anomalies in temperature and precipitation in northern Russia have been regarded as manifestations of climate change. During the same period exceptional forest fire seasons have been reported, prompting many authors to suggest that these in turn are due to climate change. In this paper, we examine the number and areal extent of forest fires across boreal Russia for the period 2002–2005 within two forest categories: 'intact forests' and 'non-intact forests'. Results show a far lower density of fire events in intact forests (5–14 times less) and that those events tend to be in the first 10 km buffer zone inside intact forest areas. Results also show that, during exceptional climatic years (2002 and 2003), fire event density is twice that found during normal years (2004 and 2005) and average areal extent of fire events (burned area) in intact forests is 2.5 times larger than normal. These results suggest that a majority of the fire events in boreal Russia are of human origin and a maximum of one-third of their impact (areal extension) can be attributed to climate anomalies alone, the rest being due to the combined effect of human disturbances and climate anomalies.

Keywords: wildfires; boreal forests; Russia; human role; climate; carbon cycle

1. INTRODUCTION

Since the last Ice Age, fire has been the primary disturbance process which organizes the physical and biological attributes of the boreal biome with consequent impact on the global carbon cycle (Weber & Flannigan 1997; Bergeron *et al.* 2001; Wirth *et al.* 2002). The physiognomy of the boreal forests is therefore largely dependent on the frequency, extent and severity of forest fires (Kasischke & Stocks 2000; Mollicone *et al.* 2002). Fire activity is strongly influenced by four factors: weather/climate; fuels; ignition agents; and humans (Flannigan *et al.* 2005; Westerling *et al.* 2006).

Since 2002 two major fire seasons have occurred in Russia, each one more severe than the previous (table 1): in 2002, 12.1 Mha of land burned, including 7.5 Mha of forests (Sukhinin *et al.* 2004); in 2003, 22 Mha burned (Schiermeier 2005) of which 14.5 Mha were forests (Goldammer *et al.* 2003). Fire activity is characterized by a large inter-annual variability and, thus, to assess real fire trends a long time-series of data would be needed. In this paper, however, we consider only recent anomalies. Mouillot & Field (2005) showed that the average annual area of forests burned since the 1950s in boreal Russia is less than 4 Mha, compared to 7.5 and 14.5 Mha burned in 2002 and 2003, respectively.

During the same recent past (2002–2005) large climate anomalies in temperature and precipitation have been observed in boreal Eurasia (figure 1), which have been regarded by some as manifestations of climate change (Thompson & Wallace 2001). Some of these anomalies (higher temperatures and/or lower precipitation) have occurred during the summer season, potentially increasing the likelihood of fire ignition and propagation; however, we note that some authors consider that fire ignition by lightning is often associated with precipitation and therefore anomalous dry weather may reduce lightning frequency (Gillett *et al.* 2004). These two pieces of evidence have been combined to point to the serious impact of climate change on Russian forests (Goldammer & Furyaev 1996; Stocks *et al.* 1998; Flannigan *et al.* 2000, 2005; Dale *et al.* 2001; Schiermeier 2005), despite the fact that it is generally recognized that fires are predominantly ignited by humans during 'normal' years (Odintsov 1995; Furyaev 1996; Valendik & Ivanova 1996; Sergienko 1999; Flannigan *et al.* 2000; Kovacs *et al.* 2004).

To determine if this trend of increasing frequency of exceptional fire seasons is a consequence only of climate change, the origin of these fires needs to be investigated (Mollicone *et al.* 2006). Wallenius *et al.* (2004, 2005) demonstrated that the historical fire regime is strongly affected by human activity, both in a boreal forest landscape dominated by *Pinus sylvestris* L. and in an unmanaged *Picea*-dominated landscape in eastern Fennoscandia. But other authors argue that in past years with climatic anomalies, between 33 and 67% of fire events were of natural origin, that is started by lightning (Ivanov 1985). Moreover, within the Russian Federation large areas of 'intact forests' still exist where it can be assumed that human influence is limited, in particular because they were designated as

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Table 1. Burned area estimates in Russia.

burned areas (km^2)	1997	1998	1999	2000	2001	2002	2003	2004
total burned areas	15 405[a]	114 914[a]	54 338[a]	97 065[a]	75 600[a]	121 419[a]	220 000[b]	n.a.
burned forest areas	7764[a]	69 063[a]	24 941[a]	51 056[a]	34 624[a]	74 794[a]	144 746[c]	28 950[d]

[a] From Sukhinin *et al.* (2004) for east of the Urals.
[b] From Schiermeier (2005).
[c] From Goldammer *et al.* (2003).
[d] Extrapolated from Goldammer *et al.* (2003) and Karpachevskiy (2004).

having 'natural fire regimes' (Aksenov *et al.* 2002). Using satellite data to localize fires, we examined fire occurrence in both these intact forests and the more human-affected or 'non-intact' forests to assess the specific impact of climatic anomalies (inside the intact forests) and the combined natural/anthropogenic impact (outside the intact forests). We measured both the number of fire events occurring in each of these strata and their areal extent (burned areas). Note that one fire event may comprise many 'fire-affected pixels' that are detected by satellite. The sum of these pixels for one fire event gives an approximate estimate of its areal extent. Given that the Russian boreal region is a huge and uniform area, the conditions are met to perform a valid statistical analysis (Johnson & Gutsell 1994).

2. MATERIAL AND METHODS

(a) *Map of intact forests of Russia*

The digital dataset of the 'Atlas of Russia's intact forest landscapes' which was generated at a scale of 1 : 500 000 (Aksenov *et al.* 2002) was combined with a land cover map of the year 2000, the GLC-2000 map (Bartalev *et al.* 2003), to delimit the intact and non-intact forest areas. The objective of this Atlas, as reported by the authors, was to delineate forest landscape areas, not strictly forest areas. A negative approach was used to discriminate between intact and non-intact forests using satellite images in which disturbances such as the development of roads can be easily detected, while the absence of any such visual signs is taken as evidence that what is left is intact (Aksenov *et al.* 2002). The intact forest areas are defined according to the following six criteria: situated within the forest zone; larger than 50 000 ha and with a minimum width of 10 km; containing a contiguous mosaic of natural ecosystems; not fragmented by infrastructure; without signs of significant human transformation; and excluding burnt lands and forest regrowth adjacent to infrastructure (Aksenov *et al.* 2002; GFW 2006). The northern limit for the Atlas excludes all tundra ecosystems. The Kamchatka region was excluded from our study zone.

In the Atlas, forest areas were derived from topographic maps where the mapping of forests was only indicative, that is they were not delineated in an accurate way. We considered another land cover map to be a more accurate data source for the identification of those areas actually covered by forests: the GLC-2000 map was produced by an international partnership of approximately 30 research groups coordinated by the European Commission's Joint Research Centre (Bartholomé & Belward 2005). The database contains land cover maps with detailed, regionally relevant map legends and a global product all based on data from the VEGETATION sensor on-board SPOT 4. Data from 1999 were used for the delineation of major forest types and from 2000 for burned areas. The Eurasian part of the map was produced in collaboration with the International Forest Institute, Moscow (Bartalev *et al.* 2003). Six forest classes were mapped at 1/112° resolution (1 km at the equator) in geographical projection. This land cover map was used to identify forested areas (by regrouping six original forest classes). In terms of accuracy, the Atlas of Russia's intact forest landscape is considered a suitable product for our study because it has been delineated from 30 m resolution imagery (Landsat-satellite type) and is derived from a set of conservative indicators of human intervention before 2000 (by excluding any visibly disturbed areas). The GLC-2000 map's quality has recently been evaluated and validated with more than 90% accuracy for Northern Eurasia (Mayaux *et al.* 2006). We know that the forests are changing over time, and indeed the Global Forest Watch produced an update of the intact forest landscape map for the northern European Russia with changes between 2000 and 2004 (P. Potapov and A. Yaroshenko *et al.* 2004, unpublished data). They estimated an areal reduction of intact forests of less than 1% over the 4-year period for most of the whole intact forest area, a reduction between 1 and 3% for approximately one-quarter of the total area and a reduction between 3 and 7% for the remaining 10%. Because the GLC-2000 land cover map is the most recent forest map of Russia, we feel it provides the best data source for our purposes as it is the least subject to forest change effects. Moreover, during the periods 1990–2000 and 2000–2005, the extent of Russia's forests has remained generally stable (FAO 2006), and consequently commission errors (fires considered wrongly as forest fires) should be very limited.

The total area covered by the Atlas is 1118 Mha, of which the total area of forests in our study zone is 543 Mha; non-intact forests represent 338 Mha and the intact forests represent 205 Mha. It has also to be noted that most of the northern forest areas are outside our study area (figure 2*a*) because the Atlas does not cover the northern Russian territory, and consequently climatic conditions within the study area are generally similar. Figure 2*a* also shows that there are large areas of intact forest in southern Russia. The overwhelming extent of the area provides a useful guide to potential historical human intervention and is fully adapted to the purpose of our study.

(b) *Most intact forests of Russia*

For the purpose of our study, a subset of the intact forest areas was selected to represent more strictly the concept of intact forests. To limit the effect of the forest border, the area where anthropogenic influences are likely to be stronger, we used two selection criteria: the size and the area-to-perimeter ratio of each individual intact area. The new subset of 'most intact forest areas' combines the largest individual intact areas, totalling up to 20% of their total area, and the individual intact areas with the smallest perimeter-to-area ratio totalling up to 20%. As some of the selected intact areas (from the two criteria) are the same, the resulting subset of 17 intact areas totals only 25% of the total area.

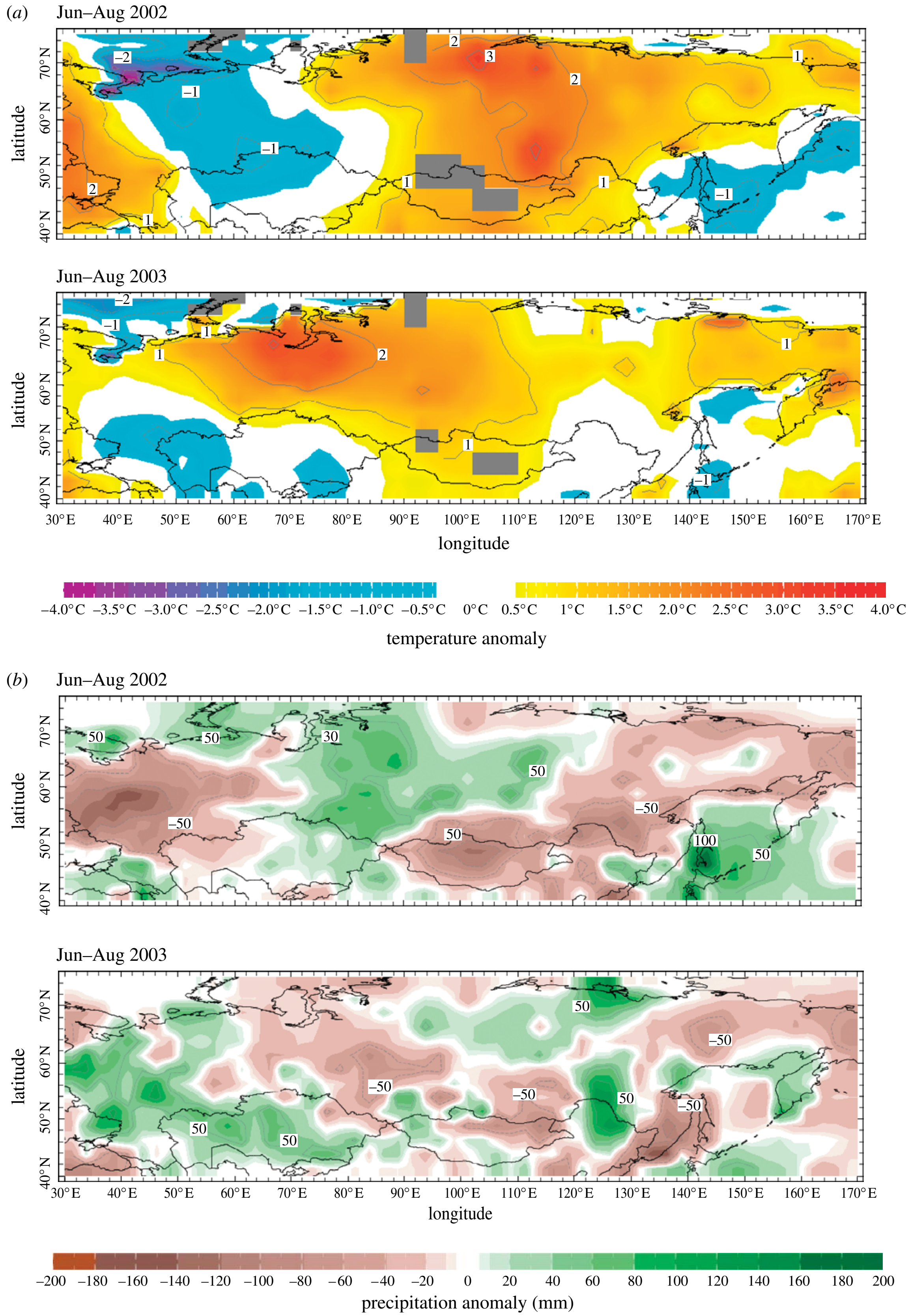

Figure 1. Climate anomalies in northern Eurasia in the summers of 2002 and 2003. (*a*) Temperature anomalies: surface air temperature anomalies (°C) on a $2.0^\circ \times 2.0^\circ$ geographical grid from the contours drawn at $\pm 1^\circ$C intervals. The base period for climatology is 1971–2000 over land regions. (*b*) Precipitation anomalies: monthly precipitation anomaly on a $2.5^\circ \times 2.5^\circ$ geographical grid. The units are millimetres (mm). Contours are drawn at ± 25 mm intervals. The period used for computing the climatology is 1979–2000. Data source: 'Climate Anomaly Monitoring System' from the US National Centers for Environmental Prediction (IRI).

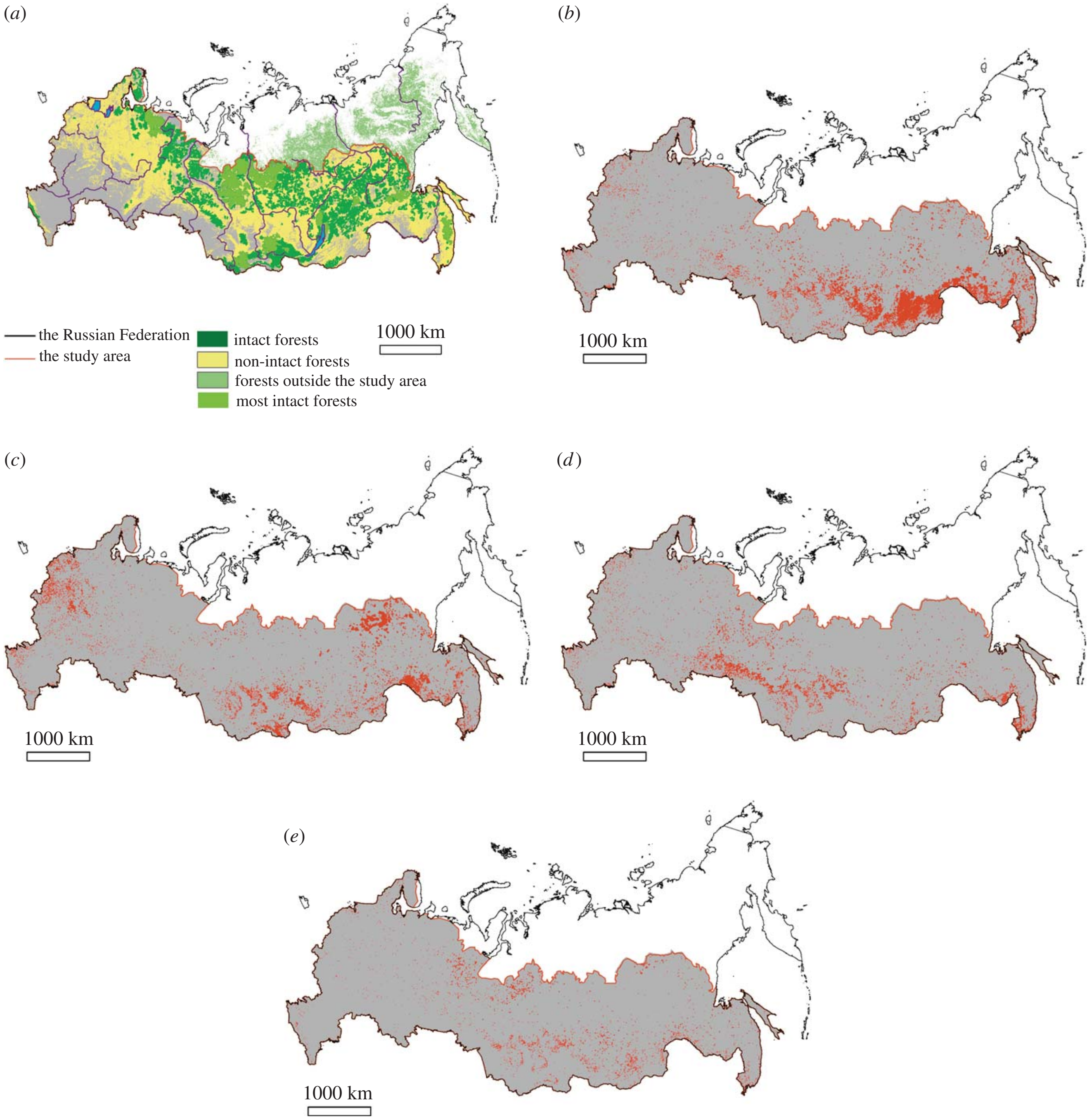

Figure 2. Map of intact forests and location of forest fires 2002–2005. (*a*) The 'intact forest landscapes' areas of the Atlas (Aksenov *et al.* 2002). Location of active fires in (*b*) 2002 (exceptional climatic year), (*c*) 2003 (exceptional climatic year), (*d*) 2004 and (*e*) 2005.

(**c**) ***Fire database for the years 2002–2005***

The 'MODIS thermal anomalies product—MODA14' (Justice *et al.* 2002) was used to derive our fire database for the years 2002–2005 (figure 2*b*–*d*). This product is a global 8-day synthesis of potential active fire pixels detected by the MODIS sensor onboard the Terra satellite, with the exact date of each fire within the dataset available. The main advantage of the 8-day synthesis for the assessment of fire events is that, as it is a temporally aggregated product, it is less constrained by spatial omissions due to cloud cover. The product is a 1 km gridded (sinusoidal projection) composite of active fire pixels (and other thermal anomalies, like volcanoes) in each grid cell over 1–8 days, which make up the compositing periods. The product contains active fires detected at 10.00 and 22.00 hours local overpass time. Fire-detection algorithms can make errors of commission (false detections) due to hot surfaces (e.g. deserts) or highly reflective surfaces (e.g. bright soils); hence, a confidence level is introduced. Such errors occur mainly in tropical and desert areas. In this work we are using the detection algorithm over dark-forested areas; we have therefore retained the two highest confidence levels (8 and 9) and rejected the lower confidence level (7). A preliminary test was carried out comparing the Terra product with that of Aqua (MYDA14) which has later overpass times of 14.00 and 2.00 hours. Within the test area, Aqua detected less than 10% more fires than Terra, with no differences in spatial distribution being found. It was therefore decided to base the study on the Terra product due to its longer period of service. In a number of parts of the world, notably the tropics, fire occurrence has a strong diurnal cycle (Eva & Lambin 1998), with a notable exception in tropical peat-land forests (Page *et al.* 2002). In the boreal forests, however, this diurnal cycle is less marked as fires tend to burn longer in this biome (Conard *et al.* 2002), so the satellite overpass time has little influence on the active fire detection capabilities. The individual fire points were extracted from the MODA14 product and remapped from sinusoidal to geographical projection (but kept as geolocated points) to allow superposition with the other spatial datasets (maps of forests and intact areas) in geographical projection at 1/100° resolution. We removed double (or multiple) fire points, that is fire points from different dates falling into the same 1/100° resolution pixel, retaining only the fire from the first date.

(d) *Fire extent and number of fire events*

For each of the 4 years (2002–2005), we first selected only those forest pixels affected at least once by an active fire. These fire-affected pixels were then separated into those that fell in or outside intact forests. Two parameters were measured in each of these two zones (intact and non intact): the fire extent and the number of fire events. The fire extent, which is simply the number of 1 km^2 fire-affected pixels, is closely correlated to the extent of the burned areas in this biome (Sukhinin *et al.* 2004; Roy *et al.* 2005; George *et al.* 2006). However, the fire-affected dataset (pixels) consists of single-date 1 km points, many of which may actually belong to the same single fire event, which once started usually carries on for a number of days and grows in spatial extent. The fire events are considered here to determine their point of origin (i.e. ignition source). To identify individual fire events, we grouped together the single-date fire-affected pixels that are spatially and temporally concurrent. This created subsets of fire-affected pixels that represent individual fire events. A fire event was attributed to the zone (intact or non-intact) in which it started, that is in which its first (temporal) fire pixel was located. We then calculated the fire event densities (number of fire events km^{-2}) within the intact and non-intact forest areas. (Fire event density does not account for fire extension, which is the main factor determining fire frequency. Consequently, there is no effective correlation between the number of fire events and the fire frequency of a forest type.)

We then estimated burned areas using annual correction factors as ratios between the number of fire-affected pixels and burned area estimates from the literature (Goldammer *et al.* 2003; Karpachevskiy 2004; Sukhinin *et al.* 2004; Schiermeier 2005). Such correction is needed due to the characteristics of the MODIS fire database.

$$\text{Correction factor} = (\text{number of fire} - \text{affected pixels})/ \\ (\text{burned area estimate from literature}).$$

Finally, we estimated the potential number and extent of natural fire events by hypothesizing that all the forests of the Russian Federation are most intact and applying the corresponding fire event density and extent.

3. RESULTS

(a) *Fire extent*

The annual totals of fire-affected pixels show that 2002 and 2003 (table 2) were severe fire years with 92 952 and 160 622 fire-affected pixels located in forests, of which 23 818 and 21 531, respectively, were in intact forests. The following years, 2004 and 2005, showed a significant fall in fire extent with 31 088 and 26 722 fire-affected pixels found in forests, of which 3413 and 6174 were in intact forests. A large inter-annual variance in the spatial distribution of major fire-affected zones can be observed (figure 2). In all 4 years, intense fire activity was concentrated in specific regions rather than being widespread over the whole territory, in particular in the fragmented forest mosaics along the south of the study area. In 2002, there were three major regions of intense fire activity: the lower Lena and Yenisey Basins and north of the Amour River. In 2003, intense fire activity stretched from east of Lake Baikal up to the Amour region. In 2004, fires were concentrated in the southern border of the Primorsky region and the lower Ob river basin. The number of fire events was also greater in 2002 and 2003 compared with 2004 and 2005 (but only 1.3–1.4 times more overall).

We found that 85% of the 23 818 fire-affected pixels in intact forests in 2002 were located within a buffer of 10 km from the perimeter of the intact areas, with a density of 0.020 fire-affected pixels km^{-2} in the buffer zones as opposed to a density of 0.008 fire-affected pixels km^{-2} in the inner areas. This suggests that the borders of intact forests are under human pressure and can also be affected by fires initiating from outside. For this reason, we used the concept of most intact forest areas to represent more strictly the intact forests.

(b) *Fire event densities*

Ratios between forest-fire event densities outside and inside intact areas ranged from 6.5 to 12.8 when considering intact forests, and from 7.9 to 14.4 when considering most intact forests over the 4 years (table 2). As expected, the intact and most intact forests are much less prone to fire events.

The fire event densities in the intact or most intact areas can be considered as an indicator (barometer) of natural disturbances by fire in these ecosystems and, indeed, in these areas the fire event densities during the exceptional climatic years of 2002 and 2003 are approximately twice (2.1 for intact forests or 1.8 for most intact forests) that of normal years. In addition, during exceptional climatic years the average size of fire events (average number of fire-affected pixels per fire event) is 2.5–3 times more than that of normal years in the intact and non-intact forest categories (table 2). Subsequently, comparing fire event densities between intact and non-intact areas, our results show that human impacts have a constant 'multiplication' effect on the fire event numbers for all years, this factor being at least 7.9. In other words, natural fire disturbances would explain a maximum of 13% of fire events or ignitions in the non-intact forests, the rest being directly attributable to humans. This 13% corresponds to the reciprocal of the fire event density ratio between most intact and non-intact forests (1/7.9).

(c) *Human role*

If we were to assume that all the forests of the Russian Federation were *most* intact (i.e. allowing the largest potential impact in terms of severity for natural fire events), then we can estimate that a maximum of 2.2 and 3.2 Mha of the 7.8 and 14.5 Mha burnt in 2002 and 2003, respectively, were due to natural factors alone (lightning and exceptional climatic conditions), the rest (more than 5.6 Mha in 2002 or 11 Mha in

Table 2. Number and densities of forest fire events.

forest type[a]	year 2002	2003	2004	2005[b]
number of fire-affected pixels[c]				
all forests of Russian Federation	100 918	187 627	36 023	36 172
forests in study region	92 952	160 622	31 088	26 722
non-intact forests in study region	69 134	139 091	27 675	20 071
intact forests in study region	23 818	21 531	3413	6174
most intact forests in study region	1988	3013	546	2879
number of fire events				
forests in study region	5929	6461	4627	3796
non-intact forests	5420	5967	4417	3477
intact forests	509	494	210	319
most intact forests	109	96	49	119[d]
fire events density (per km^2)				
forests in study region ($\times 10^{-3}$)	1.09	1.19	0.85	0.70
non-intact forests ($\times 10^{-3}$)	1.60	1.77	1.31	1.03
intact forests ($\times 10^{-3}$)	0.248	0.241	0.102	0.128
most intact forests ($\times 10^{-3}$)	0.202	0.178	0.091	0.115
fire events density ratio				
ratio non-intact/intact	6.5	7.3	12.8	8.1
ratio non-intact/most-intact	7.9	9.9	14.4	9.0
fire-affected pixels per fire events				
non-intact forests	12.8	23.3	6.3	5.9
intact forests[e]	46.8	43.6	16.3	19.3
most intact forests	18.2	31.4	11.1	24.2[f]

[a] The area extension of all forests in the study zone is 543 Mha of which 338 Mha are of non-intact forests and 205 Mha of intact forests. The total area of most intact forests (within intact forests) is 54 Mha. [b] The fire season of year 2005 was considered until 21 September 2005. [c] A fire-affected pixel corresponds to a 1 km resolution pixel in sinusoidal projection. [d] From these 119 fire events in most intact forests, 57 are located in two large intact forest areas in the Basin of Taz River where oil is currently being prospected as seen on fine spatial resolution imagery of year 2005. Indeed, intact areas were delineated using satellite imagery from the year 2000 and some areas may not be intact anymore in 2005, in particular as a consequence of the oil boom in Siberia (Dienes 2004). Fire event densities are estimated without these 57 fire events. [e] Borders of the intact forests can also be affected by fires initiating from outside their perimeter. [f] This high figure is probably a consequence of new human impact (i.e. initiated in 2005) on most intact forest areas, in particular in the Basin of Taz River.

2003) being due to a combination of human disturbances and exceptional climatic conditions as a result of increased fire hazard and propagation (table 3). For burnt areas in the normal years of 2004 and 2005, we found a total of 2.8 Mha were burnt in both years, with an estimated maximum of 0.6 and 1.6 Mha in 2004 and 2005, respectively, due to natural factors alone.

4. DISCUSSION

(a) *Validity of our results*

Our results are in agreement with an earlier study which showed that between 2001 and 2003 fires occurred mainly within the vicinity of roads or other transportation networks (Kovacs *et al.* 2004). This earlier study also showed that the extent of fires attributed to anthropogenic sources was highly variable and averaged approximately 65% in the study area (approx. 600 Mha).

We consider that our estimates of the anthropogenic contribution to the number of fire events are conservative (i.e. underestimated) for the following reasons:

— Firstly, the intact forest landscape Atlas (Aksenov *et al.* 2002) excluded all burnt areas (including areas with young forest vegetation regrowth) that were directly adjacent to a potential source of disturbance, including rivers, even though some of these fires were most likely of natural origin. This means that the intact forest areas are most probably underestimated in the Atlas. But this underestimation makes our analysis more conservative as these recently burned intact forests, which are considered in the Atlas as non-intact areas, will have the effect of lowering the fire event density in the non-intact zone.

— Secondly, our buffer analysis points to the likelihood of fires in the intact forests also being human-induced (figure 3). This would be also true (to a lesser extent) for the subset of 17 most intact areas, resulting in an overestimation of natural fire events in intact forests and, consequently, to an underestimation of the human impact.

— Thirdly, fire suppression/fighting (through human intervention) is carried out only in a limited part of the non-intact areas of the Russian Federation. This means that a single fire event is more likely to burn longer in the intact forests and therefore has more chances of being detected by satellite sensors. Again, this would lead to an underestimation of the fire event ratios between non-intact and intact forests.

— Finally, the intact forest landscape areas were delineated using satellite imagery from the year 2000, and some areas may no longer be intact in the following years, in particular as a consequence of natural resource exploration in Siberia. This also would lead to an overestimation of natural fire events in the intact forests.

Table 3. Estimation of human-induced fire extent.

year	2002	2003	2004	2005
burned forest areas of Russia from literature[a] (km^2)	74 794	144 746	28 950	n.a.
number of fire-affected pixels for all forests of Russia (km^2)[b]	100 918	187 627	36 023	36 172
burned area correction factor[c]	*0.74*	0.77	*0.80*	n.a.
corrected burned forest areas of Russia (km^2)	77 854	144 746	27 790	27 905
average fire extent in most intact areas (number of fire-affected pixels)	18.2	31.4	11.1	24.2
corrected average fire extent in most intact areas (km^2)[d]	14.1	24.2	8.6	14.9
fire event density in most intact forests ($\times 10^{-3}$)[e]	0.20	0.18	0.09	0.22
potential number of natural fire events in all Russian forests[f]	1540	1360	695	880
potential natural fire extent in all Russian forests (km^2)[g]	21 700	32 900	6000	16 400
human-induced fire extent in all Russian forests (km^2)[h]	56 100	111 800	21 800	11 500

[a] From different sources: see table 1. [b] From table 2. [c] Burned area correction factor = (number of fire-affected pixels)/(burned area estimate from literature). As the burned area estimate for 2002 (Sukhinin *et al.* 2004) is only representing the territory located east of the Urals, the burned area correction factor is underestimated for this year. The burned area estimate for 2004 is an extrapolated value. Consequently, we use the burned area correction factor of year 2003 to correct estimates of burned areas for the other years. [d] Corrected average fire extent = (average number of fire-affected pixels) × (correction factor). [e] From table 2. [f] Potential number of natural fire events in all Russian forests = (fire event density in most intact forests) × 7 640 000 km^2 (total forest area of Russian Federation). [g] Total potential natural fire extent in all Russian forests = (potential number of natural fire events in all Russian forests) × (average fire extent in intact areas). [h] Human-induced fire extent in all Russian forests = (burned forest areas of Russia) − (total potential natural fire extent in all Russian forests).

(b) *Extension of study zone and time period*

In 2003, a large number of fire events occurred in the northeast part of the Yakutia Republic which is outside our study area. This confirms (as reported in the literature) that fire frequency is also high in the northern forest areas and, particularly, in the eastern larch (*Larix sibirica*) forests and in the western Scots pine (*P. sylvestris*) forests.

An investigation stretching back over a longer period would obviously provide more evidence on the relationship between climate change, human activities and fire regimes. Unfortunately, this is not possible due to the lack of intact forest maps pre-dating the 2002 Atlas used in this study. At the same time, no suitable long-term satellite fire data exist from a single source, and it is difficult to combine fire data from different satellite sensors as they have different detection characteristics and hence will give different samples of fire activity.

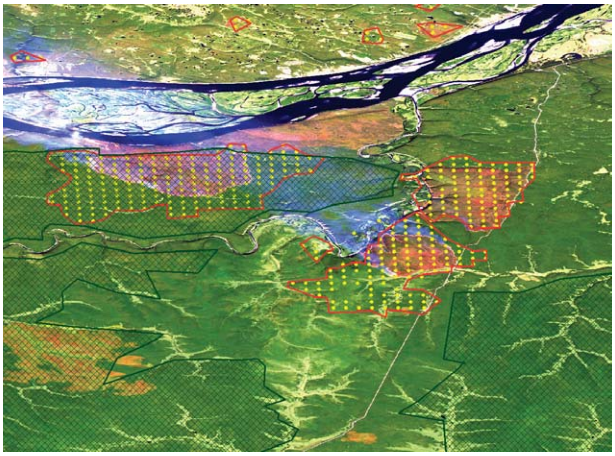

Figure 3. Example of fire events. The approximate size of the displayed image is 50 × 30 km on the ground. The background image is from the ETM+ (Enhanced Thematic Mapper) sensor of Landsat-7 satellite (30 m resolution) recorded on July 2002. On such a colour composite, forest areas appear in green, non-forest areas in light tones (tundra, bogs or swamped grasslands), water in blue (Lena river) and burned areas in reddish brown. Active fires were present at the time of the image acquisition with smoke plumes visible in white blue. The 'intact forest landscape' areas are displayed as polygons in green. Yellow dots indicate the centre of forest fire-affected pixels (originally in a grid at 1 km resolution in sinusoidal projection). Polygons in red delineate single fire events, i.e. are regroupings of fire dots with contiguous dates. In the study, the largest fire event (left side of the image) is considered as a fire event inside intact forests although it started from the river bank and may probably not have a natural origin.

5. CONCLUSIONS

These results show that, in Eurasian boreal forests as in tropical rainforests (Eva & Fritz 2003; Cochrane 2004), while climate anomalies certainly result in an increase in both the number of forest fire events and subsequent extent of forests burnt, current human behaviour is responsible for an estimated 87% of ignitions in the non-intact forests and between 72% (2002) and 78% (2003) of the total extent of area burnt. During exceptional climatic years, the fire event densities are approximately twice that of normal intact forests and the average size of fire events is 2.5–3 times more than that of normal years in intact and non-intact forests, but the human factor overshadows the direct effects of climate anomalies. This dominant human factor has important implications for the global carbon budget (Schiermeier 2005; Mouillot *et al.* 2006), in particular, in view of potential significant future increases in fires in boreal zones related to projected climate change scenarios (Flannigan *et al.* 2005).

Moreover, in recent years, human activities in this region are evolving in different directions. Indeed, while on the one hand new extensive areas of forest are under pressure due to the oil boom (Dienes 2004), at the same time forest fire management has become much less effective due to the recent economic transition of the Russian Federation (Goldammer *et al.* 2003; Karpachevskiy 2004; Achard *et al.* 2005, 2006). This gives rise to new fears of a potential large increase of the human impact on forest fire disturbances in the near future, with related consequences for carbon emissions to the atmosphere.

The clear evidence of an anthropogenic influence has important consequences for mitigation (combating fires) and feeds into the debate on whether 'natural' fires should be accounted for under a post-Kyoto mechanism.

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