Estimating Black Carbon Emissions from Agricultural Burning

Vladimir Romanenkov, Dmitry Rukhovich, Polina Koroleva and Jessica L. McCarty

Abstract High sensitivity of the Arctic region to short-lived climate forcers, including black carbon (BC), makes crop residue burning an important source of emissions. A high to moderate uncertainty in cropland burning emission estimates from remote sensing-based analyses currently exists and is problematic for establishing baseline estimates of black carbon emissions from global remote sensing products. Straw burning and possible BC emissions were estimated at the oblast level for Russia for years 2003 through 2010. A study was based on 1 km Moderate Resolution Spectroradiometer (MODIS) Active Fire Product, oblast level agricultural statistics, 1:25,000–1:50,000 scale GIS vector field maps and developing algorithms for calculating the size and intensity of fires as well as testing the accuracy of the predictions in areas with contrast land use. Both Active Fire Product and statistics methods demonstrated consistent results, including increasing fire activity in the years with additional straw surplus and the highest absolute values for vast territories with quite intensive grain production, mainly in European Russia. Straw burning can be a source of at least 1/3 total BC emissions from agriculture and grassland fires and does not appear to be the main source of total BC emissions for the Russian Federation. For regions with small number of cropland fires, the accuracy of existing remote sensing-based land cover products

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is insufficient for reliable classification of agricultural fires from satellite products. Incorrect classification of agricultural fires may exceed 25 %, increasing for the northern part of the country where forests are the predominant land cover. An improved method would be to calculate BC emissions from burned area using high resolution field masks and ground validation of fire sources in cropland areas.

Keywords Cropland burning · Remote sensing · GIS · Black carbon · Straw burning · Russia

1 Introduction

The burning of agricultural areas within Russia is a well-documented phenomenon (Soja et al. 2004), which began to receive attention within Russia as early as the 1980s (Derevyagin 1987). Local oblast-level regulations and acts which banned the field burning of crop residues were introduced in the 2000s.

Cropland burning not only results in serious environmental issues and wastes biological resources which can be used as organic fertilizers but is also an important source of emissions critical for the Arctic region with its high sensitivity to short-lived climate forcers such as black carbon (BC), which is a product of incomplete biomass combustion during crop residue burning. However, high uncertainty in emission estimates from cropland burning comparison of different remote sensing products means an analysis based on global remote sensing land cover and fire products is problematic.

For example, a recent study using different statistical and remote sensing analyses found the range of average annual BC emissions from cropland burning in the Russian Federation was 2.49–22.2 Gg for the time period of 2003–2009 (McCarty et al. 2012). This figure seems a more reliable estimation in comparison with the 2009 special report by the Clean Air Task Force (CATF), where average spring emissions assumed as high as 38.9 Gg in 2004–2007 (CATF 2009). If all straw surpluses in Russia as estimated from official agricultural reports were assumed to burn, only 24 Gg BC would be released for the above mentioned period. In reality annual burning of unused straw can produce about 6–9 Gg BC, less than 30 % of potential total BC emissions. In comparison, the total open burning consumption of straw in China is estimated to produce 10.3–10.8 Gg BC annually or about 23 % of the total output crop straw (Cao et al. 2008).

High uncertainty in these estimates is connected with the fact that few ground monitoring data are available for confirmation. Land use in Russia was subjected the largest change of the 20th century in the northern Hemisphere (Lyuri et al. 2010) when after 1990 approximately 43 million ha of agricultural lands (including 30.2 million ha of arable land) were abandoned according to official agricultural statistics. Absence of biomass removal and cultivation allows for the classification of fires on these abandoned lands as open burning but not cropland burning, and hence, uncontrolled burning. The mass scale of agricultural land abandonment and necessity of land cover product validation and update is one of many important methodological challenges to investigate crop burning in Russia. Non-uniformity of crop yields, agricultural practices, and economic incentives within all agricultural areas of Russia as well as absence of official statistical data on the total amount of crop straw burned do not allow for a management and/or policy explanation of the seasonal and interannual variations in agricultural fire activity.

Crop straw can be used as fodder and in animal husbandry, for compost production, and for household and industrial uses. At present, the proportion of the straw of grain and grain-leguminous crops used for household and fodder has substantially decreased and currently represents a minor use of crop straw. The analysis of incoming and expenditure items of straw balance shows that about 50 % of gross harvest of straw is a surplus (Rusakova 2006). Straw surplus increased from 51.4 % in 1990–1994 to 60.0 % in 2000–2004 and 63.8 % in 2005–2009, demonstrating only in 2010 a tendency to decrease in a bad harvest year resulting from the long drought in grain-production regions.

As a result, burning in the fields is a common agricultural practice used during the harvesting, postharvesting, or preplanting periods (Fig. 1).

Seasonal BC emissions from cropland burning on the territory of Russia, the Baltic countries, Belarus, Ukraine and Kazakhstan were generally highest in spring and fall, which connected with field preparations triggered by snowmelting (with a peak of more than 800 detections per day) and after harvesting before fall tillage (Fig. 2; Korontzi et al. 2006; Stohl et al. 2007).

But is straw burning the main source of agricultural fires in Russia? How can high resolution field masks be used to decrease the uncertainty of remote sensing data? How can variation in agricultural practices and economic incentives for farmers in different regions be accounted for in calculations? The present study was undertaken to answer these questions.

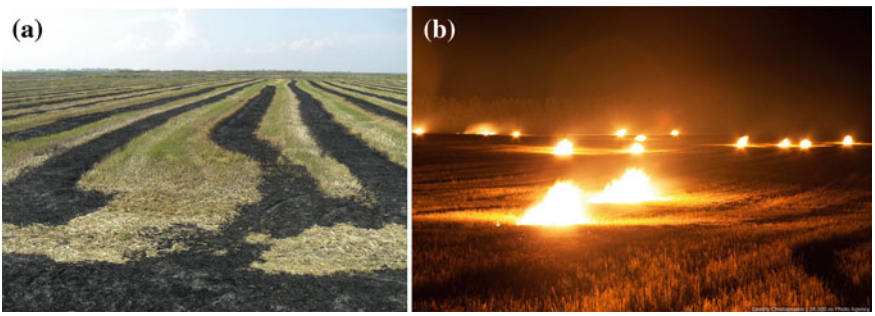

Fig. 1 Partial stubble burning in Krasnodarskij Kraj (**a**) and burning straw in windrows in Belgorodskaya Oblast (**b**) after harvesting. Figure **a** courtesy of Lothar Mueller and **b** courtesy of Dmitry Chistoprudov

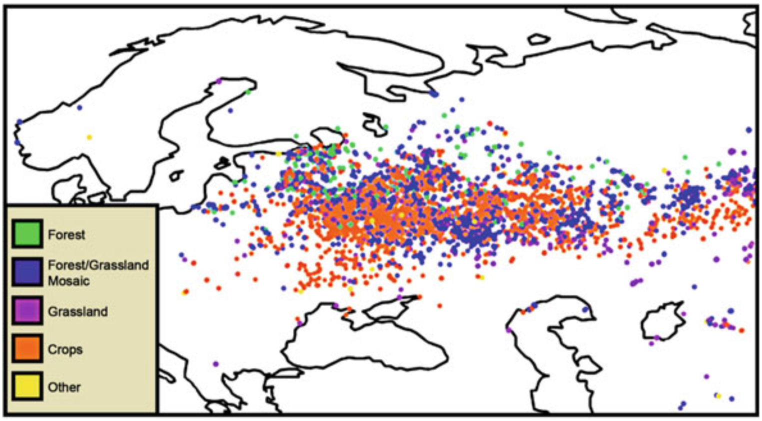

Fig. 2 MODIS active fire detections during spring 2006 classified by general land cover type across Eurasia. Late spring snow melt triggered intense field burning in April in Russia, the Baltic countries, Belarus, Ukraine and Kazakhstan

2 Data and Methods

2.1 Fire Data

The MODIS sensors, onboard the sun-synchronous polar-orbiting satellites Terra and Aqua, acquire four near-global observations daily at 1030 and 2230 (Terra) and 0130 and 1330 (Aqua), equatorial local time since 1999. The MODIS Level 2 fire product, commonly referred to as the MODIS Active Fire Data, is collected daily at 1 km resolution and includes the latitude, longitude, fire power radiation, and confidence of the fire detection. For this research, each discrete active fire point was considered to represent a burned area of 1 km^2, a common assumption that burned area is proportional to simple counts of fire pixels (Giglio et al. 2006).

2.2 Land Cover Data

Global land cover products were also considered, including the 1 km (MODIS 1 km Land Cover dataset) and 300 m (MERIS 300 m GlobCover v2.2). Cropland classifications from the MERIS GlobCover product were compared with the high resolution field boundaries for Rostovskaya, Moskovskaya, and Kostromskaya oblasts. Coordinates of active fires detected by MODIS on agricultural lands in 2003–2010 have been compared all three of these cropland land cover products (see McCarty et al. 2012).

Like the International Geosphere-Biosphere Programme (IGBP) classification schema used by the 1 km MODIS land cover dataset, the Land Cover

Classification System (LCCS) schema of the 300 m MERIS GlobCover product permits mosaic classes. LCSS land cover represents a more detailed classification compared with the IGBP as it permits 20–50, 50–70 % and >70 % of mosaic cropland within a class.

2.3 The Pilot Study Based on High Resolution GIS Field Maps

Refinements were achieved with the manual identification of croplands based on 1:25,000–1:50,000 scale field maps. GIS vector field maps have the advantage of allowing for different land cover classes in one map pixel. As a result, more precise dataset of cropland burning can be derived from the satellite fire data.

The choice of these pilot areas is connected with the fact that they are representative territories of different farming and/or cropping intensity in the absence of field masks evenly distributed for the whole agricultural area within Russia. Rostovskaya Oblast specialization is grain production based on intensive agriculture, Moskovskaya Oblast has different crop specialization with intensive technologies, and Kostromskaya Oblast is mainly a forested area and agriculture is represented by traditional crops and technologies. Rostovskaya oblast can be considered as a typical territory of the south of European Russia with 80 % of cropland from the total area and a typical field size more than 1 km^2. Moskovskaya oblast represents a region in the Central European Russia with about 50 % of arable land and a typical field size less than 1 km^2. Kostromskaya oblast is situated in the north of the European Russia with a mosaic of small fields (less than 0.5 km^2) and cropland area is about 20 % for the entire oblast.

The burned area assumption of 1 km^2 of MODIS active fire counts (Sect. 2.1) was assessed using a contemporary GIS cropland field mask. If an active fire was detected inside the boundary of a field, then the whole field was considered to have burned completely. If there were several fire points within one field over a short time period, the fire was regarded as a single burn event and burned area was the same as the area of that single field. If the fire point distance was less than 500 m from a field, it was considered a single burned field. If several fire points were situated in a line along over cropland fields over a short time period, it was not considered as an agricultural burning due to the possibility of this being a sensor anomaly or the spread of a non-cropland fire into cropland areas.

2.4 Emission Calculations

Figure 3 illustrates of the bottom-up approaches to BC emission estimations for the Active Fire based on land cover products (Sect. 2.2) and GIS filed maps (Sect. 2.3) and Agricultural Statistics analyses.

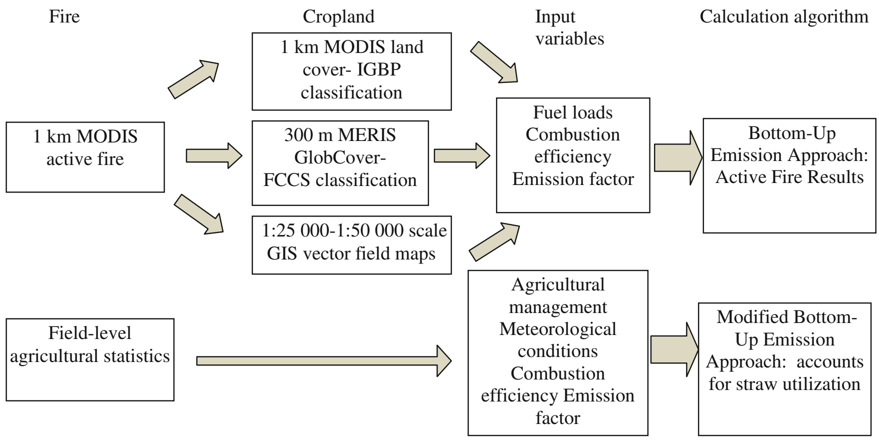

Fig. 3 Basic workflow of BC emission calculations utilized in the analysis

The estimation of possible amounts of straw burning based on the agricultural statistics approach and the active fire methodology is described in McCarty et al. (2012). A set of standard assumptions has been used in the active fire emission estimates, including the assumption of fires in those agricultural fields where cereal crops are cultivated and emission factors BC. Briefly, the equation for the BC emission calculations for the Active Fire Analysis is:

$$\text{Emissions} = A * B * CE * \text{Ebc} \tag{1}$$

where A is cropland burned area, B is the fuel load variable (mass of biomass per area), CE is combustion efficiency (fraction of biomass consumed by fire), and Ebc is the BC emission factor (mass of BC per mass of biomass burned). For this analysis, all agricultural burning in Russia was attributed to grain (wheat, barley, rye) production, which accounts for the majority of planted croplands acreages (USDA FAS 2003). Grain yield statistics was used a proxy for fuel load. The Active Fire Analysis utilized the oblast-specific fuel loadings from the official statistics and assumed a yield-to-residue coefficient factor of 1.35 to estimate fuel loads. The Active Fire Analysis used a combustion efficiency value of 0.80.

The equation for the BC emission calculations for the Agricultural Statistics Analysis is

$$\text{Emissions} = C * D * CE * \text{Ebc} \tag{2}$$

where C is annual straw surplus, D is series of correction coefficients used to account for agricultural management and agrometeorological conditions (i.e., temperature and precipitation) that can impact annual crop yield and thus straw burning. C is calculated from grain yield statistics within individual federal administrative units according to a methodology published in Derevyagin (1987).

Throughout this the manuscript, winter is defined as January through March, spring is April through June, summer is July through September, and fall is October through December, respectively.

3 Results

3.1 Emissions Based on the Agricultural Official Statistics Approach

The regions with the highest BC emission estimates can be identified with statistics approach. High values are indicative for the main grain-producing regions with the highest straw surplus. Based on this analysis, straw burning in the above regions could be a source of more than 50 % of total BC emissions.

Direct comparison of the agricultural statistical approach with the remote sensing-based fire radiative energy (FRE) and burned area analyses presented in McCarty et al. (2012) have some restrictions, as part of the fuel load is expected to be burnt next spring and seasonal contribution in straw burning have a considerable variation, both regional and interannual. However, the same trends in BC emissions are visible as in burned area analysis based on definition of croplands from the IGBP (1 km MODIS Land Cover) and LCCS (300 m MERIS GlobCover) land cover classification schemas. Estimations peaked in year 2008 with 36 % higher for statistical approach than the average emission values from 2003 through 2010, mainly as a result of 32 % increase of the total output crop straw.

Uniform high values in 2003–2009 were typical for European Russia regions: Rostovskaya oblast, Krasnodarskiy and Stavropol'skiy Krai (South Federal District), Volgogradskaya and Orenburgskaya oblasts, Republics of Tatarstan and Bashrortostan (Volga Federal District), Voronezhskaya oblast (Central Federal Distict). The highest possible emissions calculated with statistics approach from one region were found to be 6.7–9.9 % of total emissions (Stavropol'skiy Krai). Across the 7 years the highest possible emissions were calculated also for Saratovskaya oblast, Tambovskaya oblast, Samarskaya oblast, Orlovskaya oblast, Lipetskaya oblast (European Russia), Krasnoyarskiy Krai (East Siberia), Omskaya oblast, Altaiskiy Krai, Chelyabinskaya oblast, Kurganskaya Oblast, Novosibirskaya oblast (West Siberia). In East and West Siberia calculated peak of annual BC emissions from crop burning was 7.0 and 4.0 %, respectively.

Straw burning consumption is estimated at 20–27 % of the total output crop straw in 2003–2010. The last range is quite consistent in calculations since 1997. The largest contributions are European Russia oblasts (61–78 % of total burning) with less than 20 % of burning coming from West Siberia and Far East.

3.2 Emissions Based on the Active Fire Analysis

According to the Active Fire Analysis, intra-annual variations for spring, summer and fall burning were 33–70, 9–38, and 11–33 %, respectively. A slightly higher summer cropland burning in comparison with spring was calculated for years 2005 and 2007 within the LCSS cropland definition from the 300 m MERIS GlobCover product while the IGBP cropland definitions in the 1 km MODIS Land Cover product produced an equal contribution of summer and spring burning in total emissions (Table 1). Winter burning contributed for less than 0.5 % of total annual BC emissions.

The highest spring cropland burning from the active fire analysis was calculated for years 2003, 2004, 2006, 2008, 2009 and 2010. The highest annual BC emissions were calculated for years 2008 and 2009 while the lowest BC emissions for 2003 within the 8-year study period. The average BC emissions were 7.7–8.4 Gg for IGBP-Croplands, IGBP-Agriculture, LCCS-Croplands in comparison with the Agricultural Statistics Approach result of 8.5 Gg for years 2003–2010. The same is true for the interannual dynamics, with correlation coefficient of not less than 0.9 (Table 2). More than 60 % of all BC emissions, an average of 64 % for all years, occurred in European Russia. Approximately 50–79 % of all federal subjects with greater than 1 % of total BC emissions were within European Russia. On average, West Siberia was the source of 20 % of total cropland burning BC emissions, Far East Russia accounted for 9 %, and East Siberia accounted for 7 %.

The highest emissions calculated from Active Fire Analysis were found to be 7.1–15.0 % of total emissions (Krasnodarskiy Krai). The other regions which produce the highest values of emissions are Stavropol'skiy Krai as well as Rostovskaya oblast (highest among the European territories in all years except 2003, 2008 and 2009) as well as Omskaya and Novosibirskaya oblasts and Altajskiy Krai in West Siberia—vast territories with quite intensive grain production. These source regions were different than those highlighted by the Agricultural Statistics approach. In East and West Siberia calculated peak of annual BC emissions from crop burning as detected by the Active Fire Analysis was 4.3 and 9.4 %, respectively, while the highest BC emissions outside of European Russia were calculated for West Siberia only according to the Agricultural Statistics approach.

3.3 Comparison of Fire Data with Straw Surplus Statistics

For 13 oblasts of Russia which have the biggest MODIS agricultural fire counts the possible effect of air pollution and BC emission was assessed in 2003–2009. These oblasts are specialized in wheat growing. Straw surplus here was 10–15 % higher than average for all Russian grain production regions. Nevertheless, only for a few oblasts the significant relationship between straw burning estimates based on agricultural statistics and MODIS active fire counts was found. Based on these

Table 1 Average seasonal BC emissions in the Russian Federation from cropland burning as detected from Active Fire Analysis; emissions reported by four definitions of croplands, all emissions reported in Gg

Year	Season	IGBP-Agriculture	IGBP-Croplands	LCCS-Agriculture	LCCS- Croplands
2003	Winter	0.02	0.02	0.01	0.01
	Spring	2.95	2.74	2.08	0.67
	Summer	0.59	0.56	0.57	0.25
	Fall	1.27	1.23	1.31	0.50
2004	Winter	0.01	0.01	0.01	0.00
	Spring	3.34	3.01	3.23	0.72
	Summer	2.43	2.42	2.44	1.23
	Fall	1.06	1.05	0.88	0.40
2005	Winter	0.11	0.11	0.10	0.05
	Spring	2.05	1.95	1.57	0.48
	Summer	3.24	3.23	3.26	1.65
	Fall	2.27	2.23	1.99	0.90
2006	Winter	0.01	0.01	0.01	0.00
	Spring	5.22	4.79	4.91	1.24
	Summer	2.57	2.54	2.65	1.26
	Fall	1.41	1.39	1.28	0.61
2007	Winter	0.08	0.08	0.07	0.03
	Spring	2.44	2.32	1.71	0.61
	Summer	3.09	3.06	3.22	1.53
	Fall	1.22	1.19	1.04	0.46
2008	Winter	0.08	0.08	0.07	0.03
	Spring	5.77	5.36	4.74	1.15
	Summer	5.59	5.57	5.49	2.96
	Fall	2.53	2.51	2.31	1.17
2009	Winter	0.03	0.03	0.02	0.01
	Spring	7.45	6.94	6.71	1.91
	Summer	2.34	2.32	2.34	1.25
	Fall	1.43	1.42	1.34	0.65
2010	Winter	0.02	0.02	0.02	0.01
	Spring	3.18	2.93	2.78	0.67
	Summer	2.00	1.90	2.51	0.83
	Fall	1.01	0.98	0.98	0.38
Average	Winter	0.05	0.04	0.04	0.02
	Spring	4.05	3.75	3.47	0.93
	Summer	2.73	2.70	2.81	1.37
	Fall	1.53	1.50	1.39	0.63

data, in Rostovskaya oblast, Krasnodarskiy Krai and Stavropol'skiy Krai 11–16, 10–14 and 20–26 % of total straw yield can be burned in 2001–2007, respectively, with 0.3–0.7 Gg annual BC emission, $R = 0.74–0.84$ (Fig. 4). With uniform agricultural practice and grain yields within the regions statistical data here can be a reliable source of BC emission estimation. But for the biggest part of Russian regions straw burning does not appear to be the main source of BC emissions, according to this comparison.

Table 2 Annual BC emissions in the Russian Federation from cropland burning as detected from Active Fire Analysis; emissions reported by four definitions of croplands; all emissions reported in Gg

Year	IGBP-Agriculture	IGBP-Croplands	LCCS-Agriculture	LCCS-Croplands	Agricultural statistics
2003	4.82	4.55	3.97	1.43	6.57
2004	6.84	6.49	6.55	2.35	7.27
2005	7.67	7.52	6.92	3.08	7.50
2006	9.22	8.74	8.84	3.11	8.40
2007	6.82	6.65	6.04	2.64	9.08
2008	13.97	13.51	12.61	5.31	12.11
2009	11.25	10.71	10.41	3.81	11.32
2010	6.21	5.83	6.29	1.88	5.97
Total	66.80	63.99	61.64	23.61	68.25
Annual Average	8.35	8.00	7.70	2.95	8.53

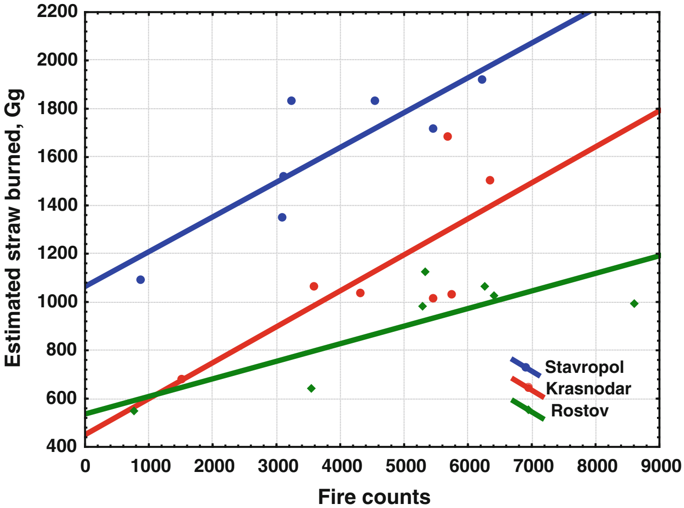

Fig. 4 Comparison of straw burning statistical estimates with MODIS active fire counts for Rostovskaya Oblast, Stavropol'skiy and Krasnodarskiy Krai in 2003–2009

This difference between the regions and their relative role as sources for BC emissions cropland burning was the reason for validation of the cropland mask, which used the cropland and cropland/natural vegetation mosaic classes both in IGBP and LCCS land cover classification schemas.

3.4 Manual Identification of Croplands

Incorrect classification can be connected with remote sensing estimates of fire point to cropland when in fact burned area is not an agricultural one (Figs. 5, 6) or missing the agricultural burned area based on the 1 km MODIS Land Cover dataset. In 2009 incorrect estimates of cropland fires with automatic pixel-based classification of land covers were 0.227, 0.421 and 0.388 for Rostovskaya, Moskovskaya and Kostromskaya oblasts, respectively (Table 3). These estimates include Active Fire points in IGBP-Agriculture land cover classification schema that do not belong to fields in accordance with field mask, Active Fire points in the fields of field mask do not belong to IGBP-Agriculture and the number of duplicate Active Fire points in the fields of field mask, so the total sum can exceed 1.0. Incorrect estimates were higher in 2010, especially for Moskovskaya and Kostromskaya oblasts. This increase in incorrect assignments of land cover classes is connected with increasing total number of fires detected in 2010, but still accuracy is not the same for the 3 regions.

Application of the 300 m MERIS GlobCover dataset did not change the fire classification results significantly. 17.5 % of the area of the region (28.8 % of the arable area) was mistakenly classified as croplands for Rostovskaya Oblast, and 14.3 % of the area of the oblast (23.6 % of the arable area) was mistakenly classified as non-arable lands; the resulting classification error for farmlands identified by MERIS was 52.4 %. 11.5 % of the area of the region (36.0 % of the

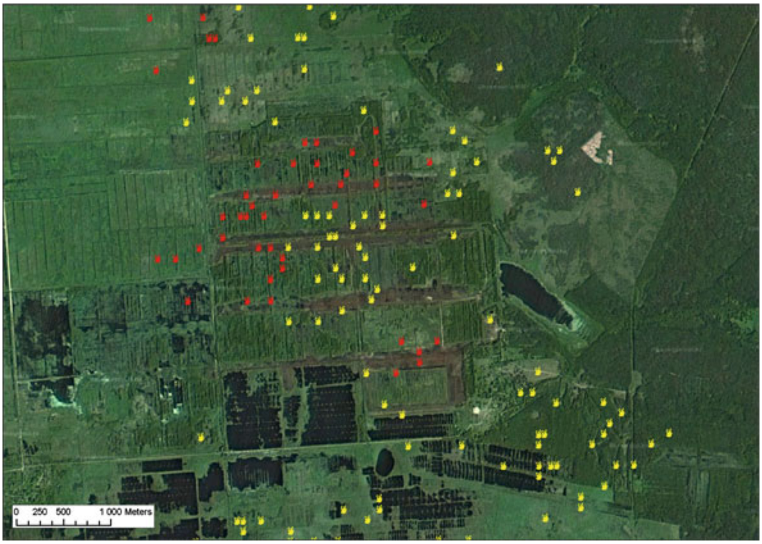

Fig. 5 Active fire points estimated as cropland burnings (*red dots*) and natural vegetation burnings (*yellow dots*) in peat bogs based on automatic land cover classification (Moskovskaya oblast)

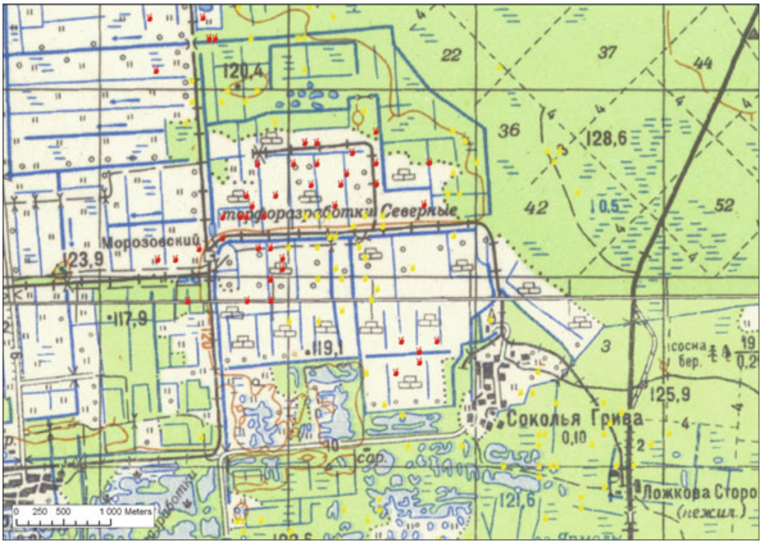

Fig. 6 The same points from Fig. 5 on a topographic map

arable area) was mistakenly classified as croplands for Moskovskaya Oblast and 12.7 % of the area of the region (39.8 % of the arable area) was mistakenly classified as non-arable lands, the resulting error of the farmlands identified by MERIS was 75.8 %. 0.8 % of the area of the region (6.1 % of the arable area) was mistakenly classified as croplands for Kostromskaya Oblast and 10.8 % of the area of the region (84.0 % of the arable area) was mistakenly classified as non-arable lands, the resulting error of the farmlands identified by MERIS was 90.1 %.

3365 MODIS active fire points were analyzed for the Rostovskaya Oblast in 2010, of which croplands accounted for 76 % of fires. Burned area calculated using the high resolution field mask produced an estimate of 269.9 thousand hectares. For 2009, burned area was calculated using the same method for approximately 440 thousand ha, with croplands contributing as much as 81 % of total active fire detections. For Rostovskaya oblast, an automatic identification of land cover classes from the 300 m MERIS GlobCover product (Fig. 7) exhibits errors of commission, illustrated in Fig. 8.

3804 MODIS active fire points recorded were analyzed for the Moskovskaya oblast for 2010, of which croplands accounted for 23 % of fires. Burned area calculated using the high resolution field mask produced an estimate of 48.2 thousand hectares. In 2009, of the 1839 MODIS satellite detections of actively flaming fires, croplands accounted for 80 % of fires with a total burned area of 95 thousand ha. For Moskovskaya oblast a 2.5 increase of uncertainty in 2010 (Table 3) was connected with incorrect classification of peat and bog lands as well as grasslands as arable fields. This feature of incorrect classification is typical for land cover data created by automatic pixel-based land cover classification

Table 3 Active fire points distribution in the pilot areas

Federal Subject Name	Total amount of fire detections	Active fire points in IGBP-Agriculture, F	Active fire points in IGBP-Agriculture that do not belong to fields in accordance with field mask, A	Active fire points in the fields of field mask	Active fire points in the fields of field mask do not belong to IGBP-Agriculture, B	The number of duplicate active fire points in the fields of field mask, C	Burned fields amount	Burned area, ha	Incorrect estimates of cropland fires, (A+B+C)/F
2009 year									
Kostromskaya oblast	142	114	11	121	18	15	106	8002	0.386
Moskovskaya oblast	1839	1398	48	1707	357	221	1486	95010	0.448
Rostovskaya oblast	4678	4426	150	4445	169	664	3781	440002	0.222
2010 year									
Kostromskaya oblast	249	126	15	162	51	27	135	7477	0.738
Moskovskaya oblast	3804	1111	418	1187	494	307	880	48163	1.097
Rostovskaya oblast	3365	3200	237	3061	98	509	2552	269941	0.264

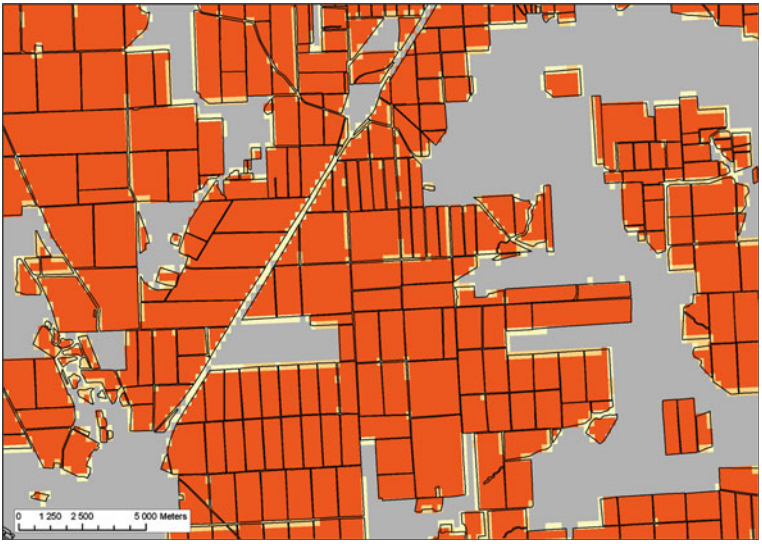

Fig. 7 Field map fragment for Rostovskaya oblast

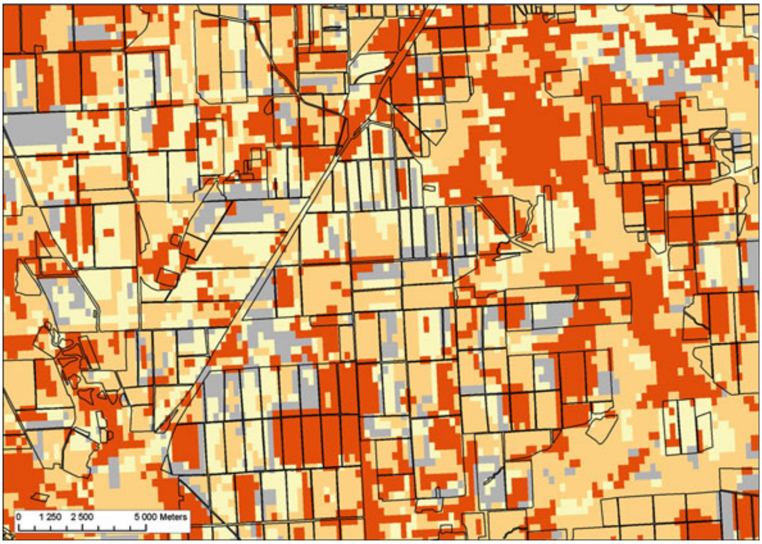

Fig. 8 MERIS 300 m GlobCover overlaid with the same fragment of field map (Fig. 7)

techniques used for global and regional satellite products produced by USGS, NASA, IIASA, Space Research Institute (IKI), etc. There was a relationship between peak of fire activity on agricultural lands and total fires in April. In year 2010, when total number of fires increased roughly twice with a 50 % decrease of

Table 4 Black carbon emission analysis in the pilot areas

Federal Subject Name	Burned area, ha	Grain yield, dt/ha	Coefficient factor of grain yield in the straw	The BC emission factor g/kg	Combustion efficiency value	BC emission, Gg		
						Calculated from the burned area	Calculated from active fire points	
							IGBP-Agriculture/ IGBP-Croplands	LCCS-Agriculture/ LCCS- Croplands
2009 year								
Kostromskaya oblast	428 611.0	17.0	1.35	0.4	0.8	0.006	0.005/0.006	0.001/0.005
Moskovskaya oblast	93 654.4	23.0	1.35	0.4	0.8	0.093	0.153/0.170	0.048/0.173
Rostovskaya oblast	7 853.9	33.0	1.35	0.4	0.8	0.611	0.471/0.472	0.254/0.482
2010 year								
Kostromskaya oblast	269 941.0	12.1	1.35	0.4	0.80	0.004	0.005/0.007	0.001/0.004
Moskovskaya oblast	48 163.0	21.6	1.35	0.4	0.80	0.045	0.087/0.104	0.017/0.179
Rostovskaya oblast	7 477.0	24.6	1.35	0.4	0.80	0.287	0.339/0.340	0.169/0.343

cropland burned area, the biggest number of incorrectly classified fires was connected with a temporarily dried bog/peatland areas.

The similar situation in 2010 was in Kostromskaya oblast, despite the fact that here boggy areas are mainly situated under natural forest canopies. 249 MODIS Active Fire points were analyzed for Kostromskaya Oblast in 2010, of which croplands accounted for 54 %. Burned area calculated using the high resolution field mask produced an estimate of 7.5 thousand hectares. In 2009, of the 142 MODIS Active Fire points, croplands accounted for 75 % of all fires and with a burned area of 8.0 thousand ha.

Comparative estimation of BC emissions for the 3 pilot areas (Table 4) demonstrate consistent results based on the field masks and IGBP land cover classification schemas in Kostromskaya oblast in 2009. The same calculation in 2010 reveals 20 and 60 % overestimation based on IGBP-Croplands and IGBP-Agriculture land cover classification schemas, respectively. For Rostovskaya oblast, IGBP land cover calculations provide more than 20 % underestimation in 2009 and 18 % overestimation in 2010. The highest errors were found in Moskovskaya oblast. Interannual variability in uncertainty is a subject of special research but it is clear that with the automatic pixel-based classification of land covers provided by the MODIS and MERIS products is not less than 30 % for the three pilot oblasts.

4 Conclusions

The BC emissions results of Active Fire Analysis are fairly consistent with the estimates from the Agricultural Statistics Approach. The highest BC emission values are indicative of the main grain-producing regions. With uniform agricultural practice and grain yields within the region statistical data, provides a reliable source for BC emission estimation.

Straw burning can be a source of at least 1/3 of total BC emissions from agriculture and grassland fires. For the biggest part of Russian regions, straw burning does not appear to be the main source of BC emissions. The peak fire activity after harvesting is indicative for the main grain-producing regions with high straw surplus. For most Russian regions, springtime straw burning shows high variability from year to year. According to Active Fire Analysis intra-annual variation for spring contribution in total annual BC emissions was 33–70 %. Substantial spatial variation of agricultural fires may be a result of different specialization, intensity of technologies, as well as percent of plowing land.

For regions with small number of cropland fires, the accuracy of existing land cover classifications made on the basis of remotely sensed data is insufficient for reliable allocation of agricultural fires. This study shows that it is preferable to make BC calculations from possible burned areas based on field masks and ground validation of fire sources on croplands.

For improving results of remote sensing monitoring of agricultural fires on the territory of the Former Soviet Union the following steps are important:

1. Delineation of uniform territories with similar strategies of using crop residues and groundtruthing of agricultural fire counts in separate fields for checking which crop residues are the main source of agricultural fires, estimate fuel load and combustion efficiency values as well as role of set-aside or fallow agricultural lands as a source of fires in open territories.
2. Electronic map of croplands as well as set-aside or fallow agricultural lands needs to be created. Otherwise incorrect classification of agricultural fires may exceed 25 %, increasing for the northern part of Russia where forest territories are predominant. As the first step this work can be performed for federal subjects in the Russian Federation with greater than 1 % of total annual BC identified by the different approaches highlighted in McCarty et al. (2012). Note that the importance of this work is higher than simply monitoring agricultural fires as it will provide more accurate burned area and subsequent BC emission estimates.
3. High uncertainty is also connected with absence of data about yield variations within the specific regions. It is impossible to make BC calculations based on average yield for the country because data from region to region can differ by more than a factor of 5. To decrease uncertainty in emission estimates, crop yield data and cropping patterns for administrative districts are necessary.

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