Multi-year black carbon emissions from cropland burning in the Russian Federation utilizing satellite fire data and agricultural statistics

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Background

- Black carbon (BC) has four effects on the Arctic climate:
  - Sunlight absorption in atmosphere;
  - Increase in cloud cover;
  - Enhanced emissivity;
  - Surface albedo.

Figure taken from Quinn et al. (2008), Atmos. Chem. Phys., 8: 1723.
Timing of BC to Arctic

• > 10X increase in BC concentrations in winter/spring vs. summer/fall
  – Sharma et al. (2004)
• Spring: sunlight + snow to melt → snow albedo feedback → larger climate impact
• In the lower troposphere, BC can interact with clouds at < 2 km altitude and can be deposited on snow
Geographic Sources of Agricultural Fires

- Function of Polar Front (AKA Arctic Front)
- “Potential Emission Sensitivity” to Arctic (>70°N)
  - Over 10 day integration
- In winter, 40°N in Eurasia and ~ 48°N in N. America
Why Burn Crop Residues?

• Residue Burning:
  1. Post-harvest burning for removal of ground-level senescent vegetation;
     • Wheat, grains, seed
     • Fall burning
  2. Pre-harvest burning biomass that accumulated over winter.
     • Spring burning
Russia: Public awareness and access to the data about crop burning

http://fires.kosmosnimki.ru/

Daily data since July 2010
Multi-Approach Analysis

**Fire Data**
- 0.5° MODIS Fire Radiative Power
- 500 m MODIS Burned Area
- 1 km MODIS Active Fire Level Agricultural Statistics

**Cropland Extent**
- 1 km MODIS Land Cover – UMd Classification
- 1 km MODIS Land Cover – IGBP Classification
- 1 km MODIS Land Cover – FCCS Classification

**Emission Calculation**
- 0.5° MODIS Fire Radiative Energy Bottom-up Emissions Approach (Seiler and Crutzen, 1980)
- Modified Bottom-up Emissions Approach; accounts for straw usage

Uncertainty Analysis
Spatial and Temporal Analysis

1. Rankings of BC emissions by federal subject;

2. Macro-regions;

3. Years 2003-2009;

4. Annual, monthly, and seasonal.
Fire Data: Fire Radiative Energy

- 0.5° MODIS Fire Radiative Power (FRP) monthly climate modeling grid product (CMG) (Vermote et al., 2009)
Fire Radiative Power (FRP)

FRP – (MW) rate of fire radiative energy emitted during combustion.

FRE – (MJ) the integral of FRP over time and space

The MODIS sensor estimates the rate of radiative energy emitted from biomass burning, referred to as the fire radiative power (FRP, units in MW), using an empirical relationship relating the difference in the “fire pixel” and “background pixel” 4 µm brightness temperatures [Kaufman et al., 1998].
Temporal Trajectories

\[ FRP(t) = FRP_{peak} \left( b + e^{-\frac{(t-h)^2}{2\sigma^2}} \right) \]
T/A Ratio = 0.42
$R^2 = 0.94$
Slope = 0.36
Bias = 121.20
p < 0.01
Fire Data: Satellite Burned Area

- MODIS Burned Area Product (Roy et al. 2002; 2005; 2008).
  - MODIS Collection 5 product (MCD45A1)
  - Both Terra and Aqua detections
  - Monthly composites
  - Julian date of burned area
  - 1 pixel of burned area ≈ 214,659 m² ≈ 21.5 ha
  - QA data not considered in this analysis
    - Qualitative rank, confidence of detection
Fire Data: Satellite Active Fire

• MODIS Active Fire Product
  – MODIS Collection 5 product (MOD/MYD14), level 2 product
  – Both Terra and Aqua detections
  – Daily data
  – 1 discrete active fire detection = 1 km² = 100 ha
  • Uncertainty of 1 km² assumption tested with contemporary GIS field mask at 1:25,000 scale.
## Defining Croplands

<table>
<thead>
<tr>
<th>Product</th>
<th>Land cover classification scheme</th>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOD12Q2 (1 km)</td>
<td>IGBP</td>
<td>Croplands</td>
<td>Temporary crops followed by harvest and a bare soil period (single and multiple cropping systems). Excludes perennial woody crops.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Croplands/Natural Vegetation Mosaic</td>
<td>Mosaic of croplands, forest, shrublands, and grasslands; no one component comprises &gt; 60% of the pixel.</td>
</tr>
<tr>
<td>MOD12Q2 (1 km)</td>
<td>UMd</td>
<td>Croplands</td>
<td>&gt;80% of pixel covered in crop-producing fields. Excludes perennial woody crops.</td>
</tr>
<tr>
<td>MERIS GlobCover</td>
<td>LCCS</td>
<td>Post-flooding or Irrigated Croplands</td>
<td>Post-flooding or irrigated shrub or tree crops; Post-flooding or irrigated herbaceous crops.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rainfed Croplands</td>
<td>Rainfed herbaceous crops; Rainfed shrub or tree crops (cash crops, vineyards, olive tree, orchard).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mosaic Cropland (50-70%) / Vegetation (20-50%)</td>
<td>Mosaic cropland (50-70%) / grassland or shrubland (20-50%); Mosaic cropland (50-70%) / forest (20-50%).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mosaic Vegetation (50-70%) / Cropland (20-50%)</td>
<td>Mosaic grassland or shrubland (50-70%) / cropland (20-50%); Mosaic forest (50-70%) / cropland (20-50%).</td>
</tr>
</tbody>
</table>
Figure 1. Comparison of the cropland extents used in this analysis; zoom-in on the southern European Russia, including the Caucasus.
Bottom-Up Approach

- $A \times B \times CE \times e_i$ (Seiler and Crutzen, 1980), where $A =$ burned area, $B =$ fuel load, $CE =$ combustion efficiency, and $e_i =$ emission factor
## Emission Factors

<table>
<thead>
<tr>
<th>Source</th>
<th>EF BC (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal communication w/ Zbigniew Klimont (IIASA; <a href="http://www.iiasa.ac.at">http://www.iiasa.ac.at</a>)</td>
<td>0.83</td>
</tr>
<tr>
<td>Turn et al. (1997)</td>
<td>0.79</td>
</tr>
<tr>
<td>Andreae and Merlet (2001)</td>
<td>0.69</td>
</tr>
<tr>
<td>McCarty (2011)</td>
<td>0.46</td>
</tr>
<tr>
<td>Average</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Table 1. Emission factors and sources used in bottom-up approach.

- McCarty (2011) emission factors derived from PM$_{2.5}$ emission factors for wheat residue burning in the contiguous U.S.
  - BC = 11.5% of PM$_{2.5}$ ef
# Fuel Loads and Combustion Efficiency

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>1540</td>
</tr>
<tr>
<td>2004</td>
<td>1890</td>
</tr>
<tr>
<td>2005</td>
<td>1880</td>
</tr>
<tr>
<td>2006</td>
<td>1900</td>
</tr>
<tr>
<td>2007</td>
<td>2020</td>
</tr>
<tr>
<td>2008</td>
<td>2380</td>
</tr>
<tr>
<td>2009</td>
<td>2270</td>
</tr>
</tbody>
</table>

Table 2. Fuel load values used in bottom-up approach.

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCarty (2011)</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 3. Combustion efficiency value used in bottom-up approach.
Fire Data: Agricultural Statistics

• Modified approach developed and published by the All-Russian Institute of Organic Peat and Fertilizers
  – Field-level residue loading: surplus after fodder and litter in animal husbandry, compost production, and for household and industrial uses.
  – Accounts for agricultural management and agrometeorological inputs.

• Emissions = C * D * CE * e_i
  – Where C is annual straw surplus, D is series of coefficients and 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 production (i.e., crop residues), CE is combustion efficiency (fraction of biomass consumed by fire), and e_i is the emission factor for species_i (mass of species per mass of biomass burned).
Different strategy of straw utilization

European Russia: Straw saved as reserve fodder and some burning of straw pushed away from the field to adjacent area.

Altai Krai: Different burn completeness for neighboring fields.
Results

• Peaks of BC emissions occurred during the spring (April – May), summer (July – August), and the fall (October);

• Highest BC emissions in all macro-regions of Russia were detected during the spring (April - June) in European Russia and West Siberia;

• The range of average annual BC emissions from cropland burning in the Russian Federation was 2.49 Gg to 22.2 Gg, with annual median value of 8.90 Gg.
1 km Active Fire BC Emissions: Monthly Variability

Figure 2. Monthly variability for Rostovskaya oblast (European Russia) and Omskaya oblast (West Siberia); IGBP-Croplands = IGBP croplands class from the MODIS 1 km Land Cover data set; all emissions reported in Gg.
Figure 3. Monthly variability for Russian Federation; IGBP-Croplands = IGBP croplands class from the MODIS 1 km Land Cover data set; all emissions reported in Gg.
**500 m Burned Area BC Emissions: Monthly Variability**

Figure 4. Monthly variability for Russian Federation; IGBP-Croplands = IGBP croplands class and IGBP-Agriculture = IGBP croplands and cropland/natural vegetation mosaic classes from the MODIS 1 km Land Cover data set; all emissions reported in Gg.
Seasonal Variability

<table>
<thead>
<tr>
<th>Season</th>
<th>BA</th>
<th>AF</th>
<th>FRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter (JFM)</td>
<td>0.45</td>
<td>0.05</td>
<td>4.98</td>
</tr>
<tr>
<td>Spring (AMJ)</td>
<td>4.55</td>
<td>3.87</td>
<td>34.1</td>
</tr>
<tr>
<td>Summer (JAS)</td>
<td>4.43</td>
<td>2.81</td>
<td>21.9</td>
</tr>
<tr>
<td>Fall (OND)</td>
<td>2.16</td>
<td>1.57</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Figure 5. Average seasonal variability of BC emissions from cropland burning for Russian Federation from Burned Area, Active Fire, and FRE approaches; IGBP-Croplands = IGBP croplands class from the MODIS 1 km Land Cover data set; all emissions reported in Gg.
Figure 6. Seasonal cropland burning in the Russian Federation from cropland burning as detected by the MODIS Burned Area Product (MCD45A1) for years 2003 – 2009; definition of croplands used: IGBP-Croplands = IGBP croplands class from the MODIS 1 km Land Cover data set.
# Summary of BC Emissions

<table>
<thead>
<tr>
<th>Year</th>
<th>Straw usage from official statistics</th>
<th>GFEDv3</th>
<th>Burned Area Analysis</th>
<th>Active Fire Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>UMd-Croplands</td>
<td>IGBP-Croplands</td>
<td>IGBP-Agriculture</td>
</tr>
<tr>
<td>2003</td>
<td></td>
<td>6.59</td>
<td>21.1 15.7</td>
<td>6.93 6.58 5.45 1.63</td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td>7.27</td>
<td>20.7 17.3</td>
<td>6.95 6.64 5.99 1.38</td>
</tr>
<tr>
<td>2005</td>
<td></td>
<td>7.51</td>
<td>27.9 23.7</td>
<td>9.13 9.00 8.40 2.32</td>
</tr>
<tr>
<td>2006</td>
<td></td>
<td>8.40</td>
<td>23.2 15.3</td>
<td>11.5 11.0 10.6 2.24</td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td>9.08</td>
<td>16.2 14.8</td>
<td>11.4 11.2 9.32 2.53</td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td>12.11</td>
<td>27.1 22.9</td>
<td>22.7 21.9 18.5 4.61</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td>11.32</td>
<td>19.0 16.6</td>
<td>13.5 12.9 11.2 2.74</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>62.27</td>
<td>155 126</td>
<td>82.1 79.1 69.5 17.5</td>
</tr>
</tbody>
</table>

Table 4. Annual, total, and annual average BC emissions from cropland burning in the Russian Federation as calculated by Agricultural Statistics, FRE, Burned Area, and Active Fire approaches; all emissions reported in Gg.
Figure 7. Source federal subjects in the Russian Federation with greater than 1% of total annual BC emissions for years 2003-2009 identified by the four approaches.
Figure 8. Annual variability of BC emissions as calculated from the Agricultural Statistics, FRE, Burned Area (BA), Active Fire (AF), and GFEDv3 approaches for years 2003-2009.
Summary

• Peaks of BC emissions occurred during the spring (April – May), summer (July – August), and the fall (October);

• Highest BC emissions in all macro-regions of Russia were detected during the spring (April - June) in European Russia and West Siberia;
  – Summer and fall emissions also significant seasonal sources and areas
  – East Siberia and Far East also source regions

• The range of average annual BC emissions from cropland burning in the Russian Federation was 2.49 Gg to 22.2 Gg, with annual median value of 8.90 Gg.