AGRICULTURAL FIRES AND ARCTIC CLIMATE CHANGE:

A SPECIAL CATF REPORT

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CATF is a nonprofit organization dedicated to reducing atmospheric pollution through research, advocacy, and private sector collaboration.

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Executive Summary

Over the past century, the Arctic has been warming at nearly twice the rate of the rest of the planet. While increases in carbon dioxide and other greenhouse gases account for much of this steep warming trend, the Arctic is also highly sensitive to short-lived pollutants—gases and aerosols that travel north from lower latitudes, impacting the Arctic climate in the near term. Black carbon aerosol, or soot, which is produced through incomplete combustion of biomass and fossil fuels, accounts for as much as 30 percent of Arctic warming to date, according to recent estimates. Springtime deposits of black carbon pose a particular threat to the Arctic climate because of their potential to accelerate melting of snow and ice.

Agricultural fires, intended to remove crop residues for new planting or clear brush for grazing, contribute a significant portion of the black carbon from biomass burning that reaches the Arctic in spring. Remote sensing of fires in non-forest lands, combined with analysis of chemical transport models and fire emissions databases, reveal that concentrations of black carbon from agricultural burning are highest in areas across Eurasia—from Eastern Europe, through southern and Siberian Russia, into Northeastern China—and in the northern part of North America's grain belt. The top emitters, in descending order, include: Russia, Kazakhstan, China, United States, Canada and Ukraine.

Regulations on agricultural burning have a poor rate of enforcement in many countries. Russia and Kazakhstan officially ban open-field burning at the Ministry level, yet fires frequently occur on agricultural (and former-agricultural) lands and often spread into adjacent grasslands and forest, creating large blazes. China also prohibits crop waste burning, but again the practice is widespread, especially in the northeast, where black carbon emissions are most likely to affect the Arctic. The United States and Canada have rules varying by state and province that aim to limit the impact of agricultural fires on air quality and surrounding property, while allowing "necessary" burning to take place.

Spring agricultural fires—though generally smaller and shorter in duration than forest fires—have a large cumulative effect on Arctic pollution levels. These burns result in transport and deposition to the Arctic during the most vulnerable period for sea ice melt; moreover lower burn temperatures smolder, emitting higher concentrations of the products of incomplete carbon combustion. Thus these fires present a clear target for mitigation. Recent advances in remote sensing and modeling techniques have improved the conditions for identifying the sources of biomass burning emissions and measuring their relative climate impact. At the same time, new agricultural technologies, such as such as crop-straw gasification and biochar, may offer promising alternatives to open-field burning of crop waste. The task of reducing black carbon's impact on the Arctic demands a concerted, region-specific, approach to agricultural fires—one that combines economically viable innovation, with increased monitoring and regulation.

Introduction

In April 2008, three teams of climate scientists[1] converged on the Northern tip of Alaska to investigate "Arctic haze"—the layers of air-borne pollutants that tint the Arctic's lower atmosphere in the late winter and early spring. Using specially equipped aircraft, the researchers flew a series of data-collecting flights over the Alaskan Arctic. What they found surprised them. Over the course of the month, the airplanes encountered up to 50 smoke plumes originating from fires in Eurasia, more than 3000 miles away. Analysis of the plumes, combined with satellite images, revealed that the smoke came from agricultural fires in Northern Kazakhstan-Southern Russia and from forest fires in Southern Siberia. The emissions from the fires far outweighed those from fossil fuels—the more expected pollution source at that time of year. "These fires weren't part of our standard predictions," says Daniel Jacob, a professor of atmospheric chemistry and environmental engineering at Harvard and a member of NASA's ARCTAS team. "They weren't in our models."

Over the last 100 years, the Arctic has warmed at nearly twice the rate of the rest of the globe. Rising temperatures have led to a steady decline in the extent of Arctic sea ice, an increase in permafrost thaw, and changes in vegetation, including the expansion of tree and shrub coverage. Like global warming generally, Arctic warming is primarily a result of the excess accumulation of carbon dioxide (CO_2) in the earth's atmosphere, which prevents increasing amounts of the earth's heat energy from escaping into space. Yet the Arctic is also highly sensitive to "short-lived pollutants"—gases and aerosols with a much shorter lifetime than CO_2—that travel north from more populated mid-latitudes into the Arctic air mass, affecting the local radiation budget in the near term.

While scientists have long known that forest fires contribute a significant portion of Arctic pollution, especially in the dry summer months, they have paid less attention to

[1] These included NASA's "Arctic Research and the Composition of the Troposphere from Aircraft and Satellites" campaign (ARCTAS), the NOAA's "Aerosol, Radiation, and Cloud Processes Affecting Arctic Climate" field experiment (ARCPAC), and the Department of Energy's "Indirect and Semi-Direct Aerosol Campaign" (ISDAC). The missions were organized under the International Polar Year program of 2007-2008.

agricultural burning. These smaller, man-made fires—usually intended to remove crop residues for new planting or clear brush for grazing—often spread onto adjacent land, threatening lives and property and producing hazardous air quality. When set in the spring, the fires pose a particular danger to the Arctic climate. Plumes deposit soot, or black carbon, onto snow and ice, increasing the surface absorption of solar energy and potentially hastening the onset of the spring melt.

International curbs on agricultural fires could reduce the load of short-lived pollutants reaching the Arctic and buy some time for benefits of CO_2 reductions to kick in. Yet any mitigation strategy will first require a clear picture of the location and extent of these fires, their seasonal occurrence, as well as their contribution to climate change. Much of this information is currently unfolding. The following pages offer a preliminary view.

Biomass burning smoke layer above Western Alaska, April 6, 2008, courtesy of Cameron McNaughton for ARCTAS.

Haze over Brooks Range Alaska, April 13th, 2008, courtesy of Cameron McNaughton for ARCTAS

Biomass burning and Arctic black carbon—underrated agents of climate change

Humans have been burning vegetation for thousands of years, as a source of heat and cooking fuel and as a tool in cultivation. In the late 1970s scientists began to recognize open biomass burning (a term that refers to both prescribed and wild fires) as a significant factor affecting global pollution and climate (Langmann 2009, Seiler 1980). As vegetation burns, it releases stores of CO_2, along with other greenhouse gases, into the atmosphere. It also emits large quantities of microscopic aerosol particles, including black carbon or "soot." Soot particles are formed through the incomplete combustion of wood and other biomass fuels, as well as fossil fuels. In populated areas, particulate matter (PM) that contains soot can induce or aggravate respiratory diseases—a fact that has led to regulations on fossil fuel emissions and open-field burning in many industrialized countries. Black carbon's role in global warming has regained attention in the last several years, as researchers have acquired more sophisticated tools for climate modeling and atmospheric measurement.

Black carbon-containing PM, transported to the Arctic via smoke, remains in the atmosphere for about a week. During that time, it can disturb the local climate system in a number of ways. First, as black carbon settles in the Arctic's troposphere—within and above the "haze" layer—it absorbs solar radiation that would otherwise reach the surface. As the troposphere warms, it emits long-wave radiation downward. The net effect is a heating of the surface (Quinn et al. 2008). Black carbon also affects the Arctic climate by reducing surface reflectivity, or albedo. As soot particles "wash out" of the atmosphere, they land on snow and ice, darkening surfaces in ways that are usually imperceptible to the human eye, but even these small concentrations are able to absorb significantly more of the sun's rays. As the surface warms, the snow crystals coalesce into denser, coarse-grained structures that further absorb energy and can speed the pace of melting. Studies of Arctic snow samples from Siberia and Greenland reveal that, during the melting process, soot frequently gets redistributed vertically within the snow pack rather than washing away with the melt water; thus, as snow melts, the particles can remain on the surface, intensifying their effect on albedo (Warren 2008). Newly exposed ocean and land surface, in turn, absorb more solar radiation, reinforcing the heating effect. This series of climate forcing reactions, known as "surface albedo feedback," has a maximum impact in spring, when sunlight hours are increasing and seasonal snowmelt is underway (Flanner et al. 2007).

Ice and snow reflect solar radiation.

Black carbon deposits darken surface and reduce reflectivity.

Source: NASA/GISS

While there remains uncertainty about the magnitude of the impact of black carbon's effects on snow, it could account for about 10% of man-made global warming and 30% of Arctic warming (Flanner et al., 2007). Because of its combined heating of the Arctic atmosphere and surface, black carbon may warm the Arctic more than any other agent except CO_2 (Zender 2007, Flanner et al. 2007). As an aerosol, black carbon also contributes to cloud formation, which has a cooling effect on the surface; however, the contribution of black carbon to Arctic clouds remains unclear (Lubin and Vogelmann 2007, Quinn et al. 2008).

According to a 2000 emissions inventory, biomass burning contributes an estimated 42% of the world's black carbon a year (Bond 2007) and is the dominant source of black carbon reaching the Arctic, with contributions increasing in *el Niño* years, due to strong wildfires (Flanner et al. 2007). In 1998, an *el Niño* year with intense boreal forest fires in Canada and Eastern Siberia, annual mean black carbon concentrations in snow over Greenland were 44% higher than in 2001, a normal/non- *el Niño* year; in the summer months, the fires accounted for 60% of black carbon in 1998, and 36% in 2001 (Flanner et al. 2007).

These forest fire numbers do not reflect the relative contribution of anthropogenic—and specifically, agricultural—burns to overall biomass emissions. Boreal fires, because of their size, duration and proximity to the Arctic, have had a clear and measurable impact on Arctic pollution levels—an effect that appears to be worsening as a result of climate change (Randerson et al. 2006, Soja et al. 2007). At the same time, there is increasing evidence that agriculture-related fires have been underrated as a source of Arctic black carbon. Although these fires are substantially smaller than forest fires, their proportional black carbon emissions may be greater. Smoke samples taken over Alaska in April 2008 showed "higher enhancement ratios" of black carbon in the agricultural fire plumes than in the forest fire plumes—a reflection of the fact that agricultural fires burn at lower temperatures and tend to smolder, emitting higher concentrations of the products of incomplete carbon combustion (Warneke et al. 2009). Recent pollution episodes in the Arctic suggest that agricultural burning presents a global environmental threat that may be growing due to a combination of climate and human societal factors.

How spring smoke gets to the Arctic

In the spring of 2006, two years before the surprising observations over Alaska, researchers on the Norwegian island of Svalbard encountered the highest black carbon levels ever recorded in the European Arctic. The smoke appeared in late April and early May. "Many of us first mistook the plumes for pollen," explains Andreas Stohl, a senior researcher at the Norwegian Institute for Air Research. Aerosol optical depths—a measure of daytime visibility—were also the highest on record for that location, which lowered visibility and strongly disturbed the radiation transmission in the atmosphere. Even more unusual, the soot had visibly discolored the snow, reducing surface albedo.

Satellite data, combined with a particle dispersion model known as FLEXPART, traced the smoke to biomass burning in Eastern Europe. News reports in the *Baltic Times* described agricultural fires, set by farmers in western Russia, Belarus and Ukraine, that burned out of control, igniting nearby forestland and even killing five people in Latvia (Stohl et al. 2007). Smoke from the fires also caused weeks of severe pollution in Finland, where scientists measured hazardous levels of fine particulate matter in the air (Antilla et al. 2008).

April 26, 2006, View above Svalbard, Norway, prior to the arrival of smoke plumes from agricultural burning in Eastern Europe.

May 2, 2006, Same view over Svalbard following the arrival of smoke from Eastern European agricultural fires. Photos, courtesy of: Ann-Christine Engvall.

A number of climate conditions determine the effective transport of smoke plumes to the Arctic. Meteorologists have found that in order for gases and aerosol particles to penetrate the closed dome of frigid air over the Arctic troposphere, the source region must have similarly low potential temperatures (Carlson 1981, Iversen 1984, Barrie 1986). Areas below 40 degrees latitude, which fall short of the Arctic front, are thus less likely to affect Arctic pollution levels because average temperatures there tend to be too warm; it is the colder parts of the northern hemisphere that primarily contribute to wintertime "Arctic haze." In the case of biomass burning emissions, the weather in the source region must be suitable for vegetation to burn. In 2008, low snow amounts in Siberia and Russia caused the fire season to start early, in March, when temperatures were still cold. The cold air from these high-latitude locations provided a pathway for smoke to travel into the lower troposphere of the Alaskan Arctic (Warneke et al. 2009).

A different but analogous set of circumstances occurred in 2006. That year, spring temperatures in the European Arctic were unseasonably warm. At the same time, the Baltic countries were experiencing an unusually late snowmelt, which required farmers to wait until the end of April/beginning of May to prepare their fields for sowing. Thus, when the fires began, temperatures between the source region and the receptor region were close enough to facilitate the conveyance of the soot-laden smoke into the Arctic (Stohl et al. 2007). Given that Arctic temperatures are rising at a much faster rate than those in lower latitudes, Stohl points out, "Such transport conditions may become more frequent in the future."

Within the constraints of temperature, certain parts of the world are more efficient purveyors of short-lived pollutants to the Arctic than others. Scientists working with the Task Force on Hemispheric Transport of Air Pollution (HTAP)[2] have developed simulations of how gas and aerosol concentrations in the Arctic respond to emissions from different areas in the Northern Hemisphere—Europe, East Asia, South Asia and North America (Shindell et al. 2008).

Their results, though incomplete because Russia was not included in the model runs, show Europe as the lead source of emissions to the Arctic (outside of Greenland). In all seasons, they found that Arctic surface levels of black carbon, as well as sulfate and carbon monoxide were "substantially more sensitive to European emissions than to those from other regions" (Shindell et al. 2008). East Asia also contributed a major portion of black carbon to the Arctic and was comparable to Europe in its effects on tropospheric black carbon in spring. North American emissions, meanwhile, dominated pollution levels in Greenland. In the non-winter months, Stohl (2006) observes, Greenland's high topography allows the inflow of air from relatively warm and moist source areas in North America—and to a lesser extent in East Asia—to occur more easily than in the rest of the Arctic (Shindell et al. 2008).

Modeling data, so far, only partially align with Arctic observations. The omission of Asiatic Russia/North Asia as a source region, in particular, prevents the models from predicting the extensive biomass burning emissions that appeared over northern Alaska in

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[2] HTAP is a project under the 51-nation Convention on Long-Range Trans-boundary Air Pollution

April 2008. The severity of recent smoke plumes in the Arctic has challenged researchers to ask whether agricultural fires might be contributing to a hitherto undetected pattern of Arctic pollution. Determining the answer to this question requires linking chemical transport models and emissions data to real-time evidence of fire occurrences around the globe.

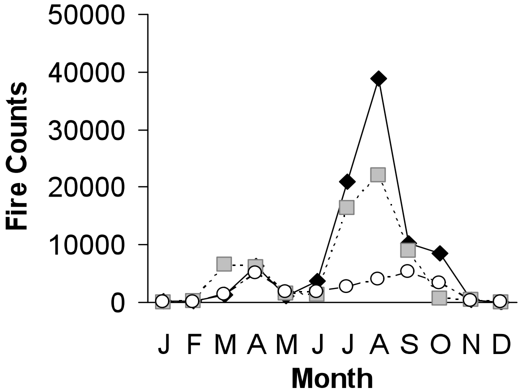
Locating fires in space and time

In recent years, major advances in satellite technology have enabled scientists to track subtle changes on the earth's surface that might indicate the effects of climate change or pinpoint pollution episodes. An instrument, known as the Moderate Resolution Imaging Spectroradiometer or MODIS, has been designed for many purposes, including detection of global fire activity. Set aboard two polar-orbiting satellites, MODIS provides daily observations of large and small fires with a high degree of accuracy. Careful analysis of these images, in combination with land-use maps, produces a vivid picture of the global distribution of burning including burning in agricultural types (or areas).

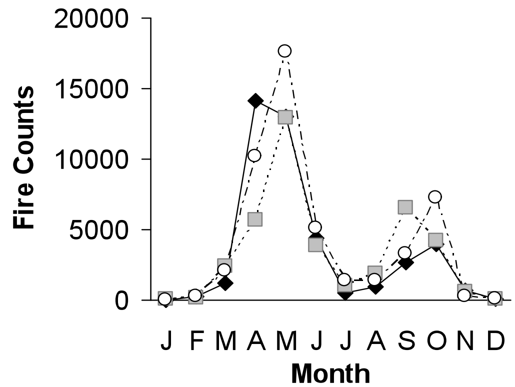
A comprehensive study of MODIS data, collected between 2001 and 2003, shows that agricultural fires accounted for about 10% of all fires globally. The bulk of these fires (94%) occurred in the Northern Hemisphere. Over the three-year period, the largest number of fires took place in Eastern Europe and European Russia, while the second largest concentration was located in Asiatic Russia and central and northeast Asia. North America had the third highest percentage of agricultural fires (Korontzi et al. 2006). Relatively few fires took place in Western Europe, where bans on open-field burning have been enforced since the 1980s.

Seasonal burning peaks differed across the three regions. In Eastern Europe and European Russia, for instance, the greatest amount of agricultural burning took place in August, following the harvest of winter and spring wheat; a smaller burning spike occurred in spring, when farmers prepare their fields for planting. In Asiatic Russia, along with Kazakhstan and northeastern China, agricultural fires peaked in spring (March/April), but also showed an increase in late summer and early fall (Aug-Oct). North America had maximum burning periods in both spring and fall.

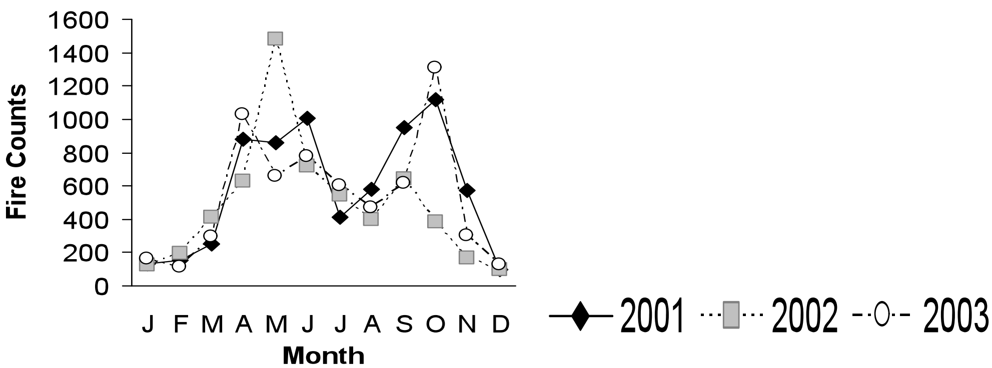
Eastern Europe and European Russia



Asiatic Russia, Central and Northeast Asia



North America

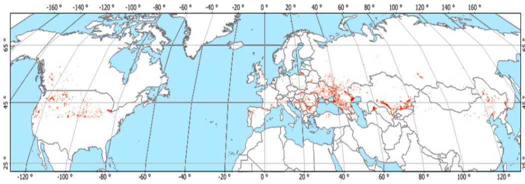


Source: Korontzi et al., 2006.

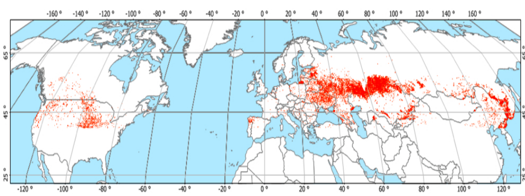
As the figure above illustrates, there was significant variability in fire counts within seasons from year to year. While 2003 was a low fire year in all seasons for Eastern Europe, due to adverse weather conditions (Korontzi et al. 2006), it was a high fire year in spring in Asiatic Russia. In North America, spring burning peaked late in 2002, because of unseasonably late snowfall, and was more intense than in spring 2001 and 2003.

Set against this data, the Eastern European fires in spring 2006 represent another example of variation within a general spatial-temporal pattern of agricultural burning. The smoke observed over Svalbard at the end of April/beginning of May corresponded to a late spring spike in cropland burning in Western Russia, Ukraine and the Baltic countries. The maps below—produced by Arthur Lembo, assistant professor of geology and geoscience at Salisbury University, using MODIS active fire and land use data—show the intensification of agricultural burned area from March to May in each year between 2004 and 2007. The images reflect only the cropland fires north of 40 degrees latitude that have the potential to impact the Arctic in the near term.

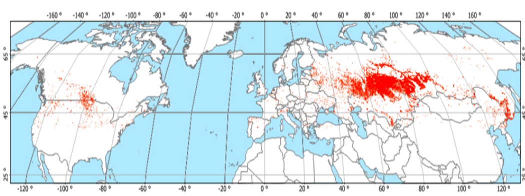
March 2004



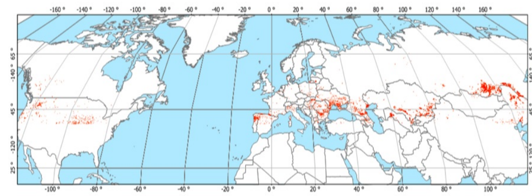
April 2004



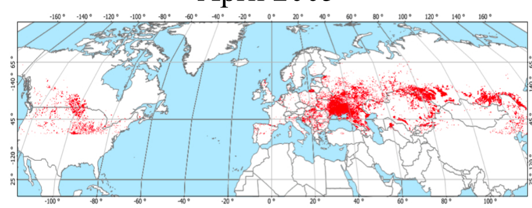
May 2004



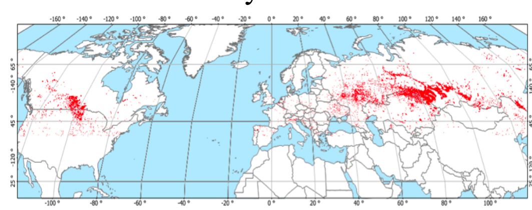
March 2005



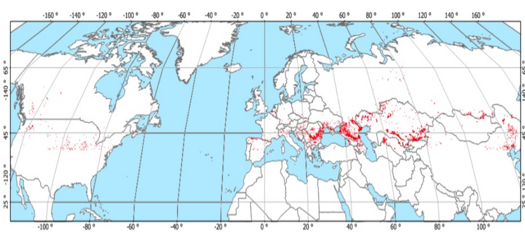
April 2005



May 2005

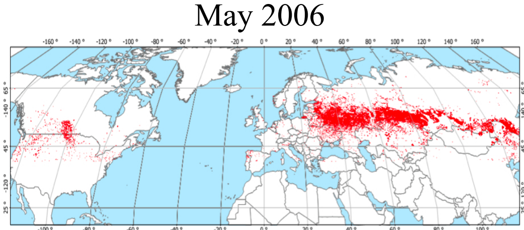


March 2006



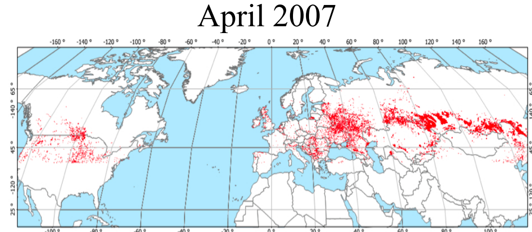
April 2006

May 2006

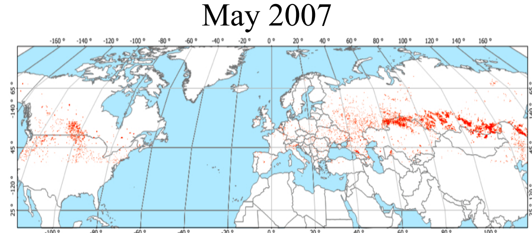


March 2007

April 2007

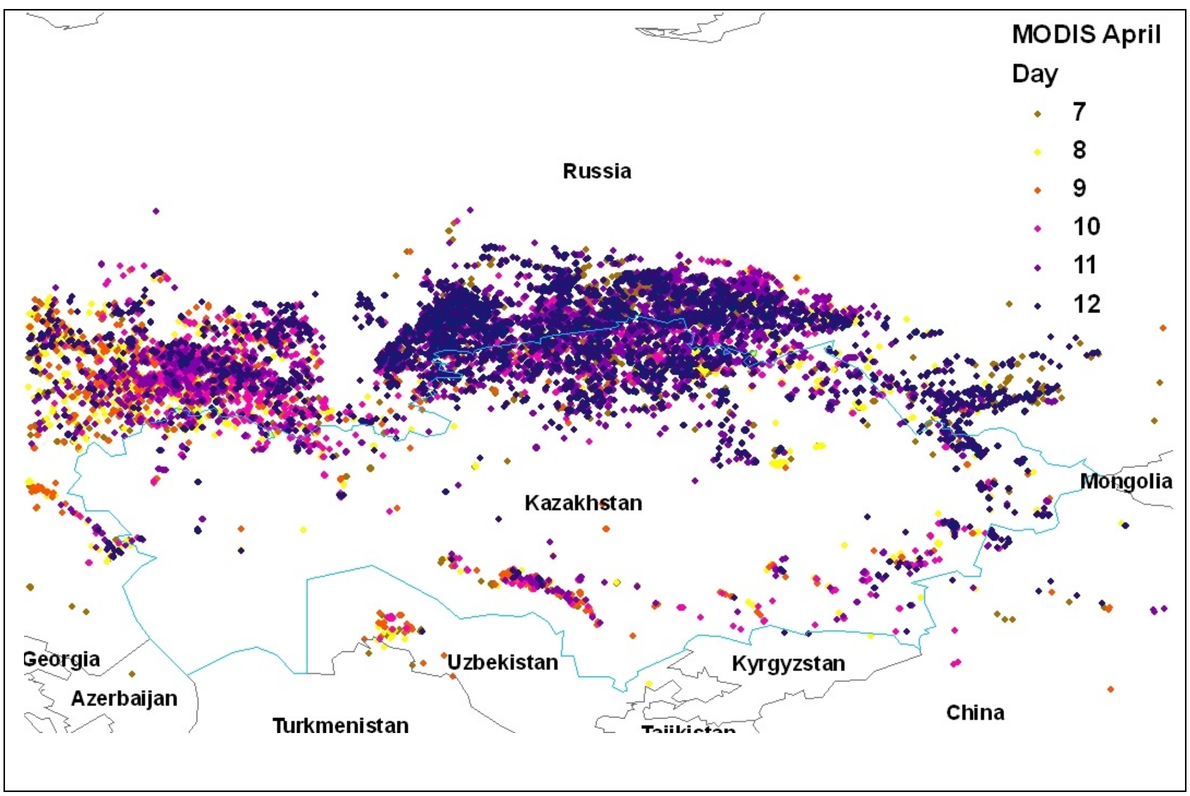


May 2007



Fire activity generally increased across southern Russia and into the northeastern corner of China, from early to late spring in all four years, but the pattern in 2006 is particularly pronounced. In Eastern Europe, April was the peak month for spring agricultural fires from 2004 to 2006, but March was the peak month in 2007. In North America, the belt of croplands extending from Alberta and Saskatchewan, Canada into the northern Great Plains states in the US also underwent significant, though less extensive, spring burning between 2004 and 2007, with fires occurring mostly in April and May.

Researchers have begun looking closely at the Kazakhstan fires that produced the April smoke plumes in the Alaskan Arctic in 2008. MODIS data suggest that 2008 was in fact an exceptional year of burning on the Kazakh-Russian border. The map below reflects fire activity for each day between April 7 and April 12, 2008. Allowing 7-9 days for smoke transport to the Arctic, the fire spots below correspond to the plumes observed over Alaska during the third week in April.



Produced by Amber Soja, for NASA's ARCTAS mission.

According to MODIS records for Kazakhstan, April 2008 accounted for 42% of the total number of fire detections in April over the previous 6 years; and more than 60% of the fires detected during the month were concentrated in two 4-day periods (April 10-13, 19-22).

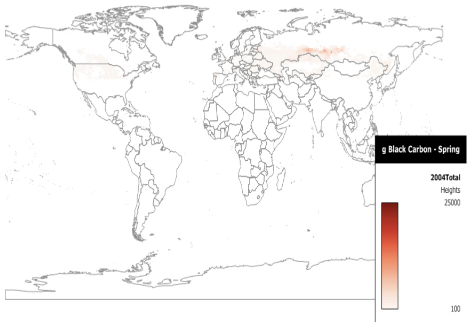
Calculating fire emissions

Periodic years of unusually intense spring burning pose a clear threat to the Arctic climate. Researchers currently use global fire emissions data to compute emissions, including those of black carbon. The Global Fire Emissions Database (Randerson et al. 2007)[3] provides estimates of fuel loads, combustion completeness and fire emissions of trace gases and aerosols for monthly burned areas (1 degree x 1 degree) detected by satellite. The proportion of burned biomass emitted as black carbon in any given fire depends on both burning efficiency (which is related to moisture levels in the crop waste and fire temperature) and the type of crop residue (i.e. wheat, barley, flax, corn, soy, etc.).

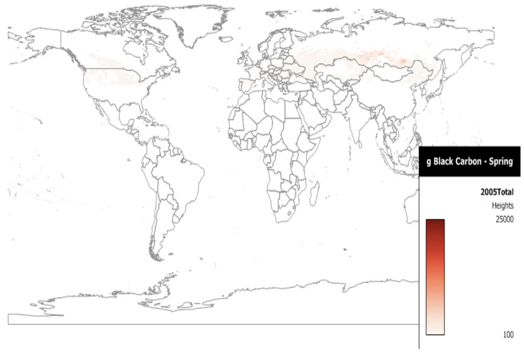
Clean Air Task Force consultants, Madhura Kulkarni and Arthur Lembo, have overlaid global fire emissions data onto agricultural fire maps for the area north of 40 degrees N latitude. Because the Global Fire Emissions Database does not yet have a high level of accuracy for agricultural areas and the spatial resolution of the data is low (1 degree x 1 degree), the maps below represent only preliminary approximations of black carbon distributions for spring 2004-2007.

[3] The most recent version of this data set is GFED, Version 2.1, compiled by Randerson, J. T. et al. 2007. The new version under development , GFED V. 4, is expected to improve accuracy and reduce uncertainties.

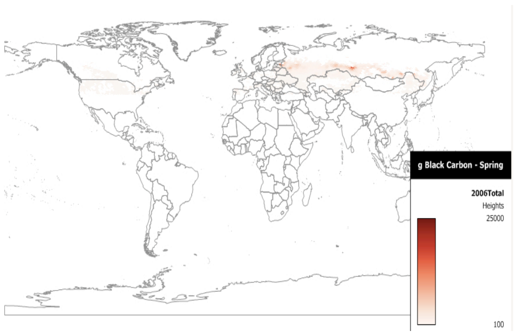
2004



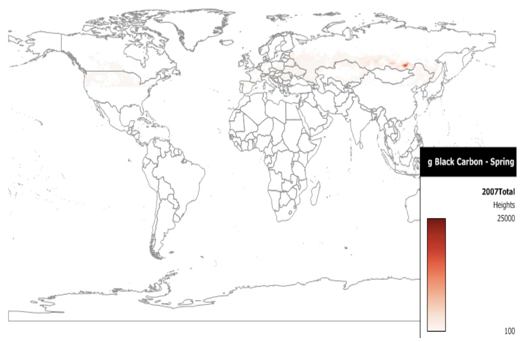
2005



2006



2007



While quantitative estimates of black carbon emissions, by country, are not yet complete, initial results identify a number of nations as clear leaders. Russia contributed 78-84% of the world's springtime black carbon from agricultural fires between 2004-2007. The other top emitters included: Kazakhstan, China, Canada, and the United States. [4]

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[4] These calculations, made by Kulkarni and Lembo using GFED black carbon emissions and MODIS land use data, show Eastern European countries with a lower than expected black carbon contribution. Although global data provided by Zbigniew Klimont (compilation of public and unpublished GAINS datasets by the International Institute for Applied Systems Analysis) show Ukraine with the highest annual amount of burned crop waste, the recent black carbon estimates rank the Ukraine below the US and Canada. The discrepancy could arise from measurement inaccuracies or from other factors, such as burning conditions and crop type. Furthermore, as Stefania Korontzi points out, most of agricultural burning in Ukraine takes place in the summer months.

Country	Average Spring BC in Gigagrams (Gg), 2004-2007	Average Spring BC as percent of total global emissions, 2004-2007
All Countries	47.7 Gg	
Russia	38.9 Gg	81.4%
Kazakhstan	2.63 Gg	5.5%
China	1.41 Gg	2.9 %
USA	0.60 Gg	1.3%
Canada	0.56 Gg	1.2%
Ukraine	0.35 Gg	0.7%

Agricultural-Source Black Carbon (BC), by country, in areas north of 40 degrees latitude during months of March, April, May. Source: Madhura Kulkarni and Art Lembo for CATF, April 2009.

Across these countries, the contexts of agricultural burning vary widely, and governments have taken different approaches toward regulation and oversight. In the locations where spring fires are most pervasive, information on burning practices remains opaque—shrouded in part by terminological inconsistencies and bureaucratic indifference. The remaining discussion describes some of the conditions that contribute to agricultural burning in the major black carbon-emitting regions and points to issues in need of further investigation.

Land-use change and fire control in post-Soviet Russia and Kazakhstan

The collapse of the USSR in 1991 brought an end to the socialist command economy that had dominated agricultural production for decades. In the absence of state subsidies, the large farming cooperatives that had supported Soviet industrial society were abandoned, leading to the re-growth of vegetation across much of the countryside. As smaller private enterprises emerged, they faced a changed landscape; cultivated fields now existed alongside wild grasslands and dry brush, creating ideal conditions for fire (Dubinin et al. 2009).

During the same period, Russia's centralized fire management system steadily weakened, due to declining government funds and attention. "Under the Soviet system, all fires were viewed as destructive," explains Johann Goldammer, a senior scientist at the Max Planck Institute for Chemistry and the director of the Global Fire Monitoring Network; "[The government] devoted 8000 airplanes to fire control." Yet, by 2003, Russia accounted for an estimated 36% of the world's agricultural fires (Korontzi et al. 2006), and today, the Russian Federation has the largest forested and non-forested territories in the world in which natural and human-caused wild fires are occurring on a large scale (Goldammer 2006).

Determining the causes of large vegetation fires in Russia presents a challenge. Official sources maintain that a year-round ban exists on all agriculture-related burning under the Preventative Firefighting Regulations of the Russian Federation (PFR 01-03).[5] Yet there is little evidence of enforcement. According to Johann Goldammer, who has spent a number of years investigating fires and fire management in the former Soviet Union and elsewhere: "There are lots of unknowns. What may start out as a small agricultural fire, intended to clear grasslands for pasture, or prepare a garden for spring planting, can quickly spread across the grassy steppe and encroach on adjacent forest." An increasing number of fires, he points out, stem from leisure-time negligence: "People go into the countryside, they build campfires for barbeques, maybe they are drinking… and then they leave, not worrying about the consequences."[6]

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5 According to Burenin Nikolaj Sergeevich, paragraph 327, section X of PFR 01-03, states that: "the burning of stub land and crop residues, as well as bonfires in the fields, are prohibited" (personal communication). However, this ministry document is not supported by higher level laws and/or President's orders and does not contain definitions of responsibility and fines.
Mr. Sergeevich identifies himself as "head of the department for scientific-metholodological grounds in the field of environmental impact, transboundary transfer and state accounting."

6 Goldammer cites a fire peak that occurred on International Women's Day, 2008, in Siberia, when "fires were popping up like mad!": "After they cook and clean, the women go out into the countryside to celebrate. They build campfires and drink together. The fires are forgotten. …. They live in cities

Similar conditions have led to an increase in fire activity in Kazakhstan, a former Soviet republic on Russia's southern-central border. Over the past decade, a lack of financing for Kazakhstan's Aerial Forest Fire Service has diminished the government's capacity to detect and monitor fires, allowing increasingly severe blazes to burn unchecked. "Rural people on farm land adjacent to forests tend to burn off vegetation, and such fires often accidentally spread to forests" (Kushlin et al. 2004, cited in Goldammer 2006).

Approximately 20% of Kazakhstan's land area consists of steppe—semi-arid grass-covered plains that burn easily. According to researchers at the Sukachev Institute (the Siberian branch of the Russian Academy of Sciences), agricultural activities are the major cause of steppe fires; the ignition sources include not only crop-residue burning, but also sparks from tractors, combine harvesters and cars.

> A mass wildfire season, mainly in plain and little-forested areas, begins as early as mid-March in Kazakhstan, with fires consuming cured grass very rapidly. These fires are the greatest threat to still existing natural plain forest and forest shelterbelts. Steppe fires are mass fires caused by agricultural burns (Sukachev Institute, personal communication, 2009).

In spring of 2008, the Kazakhstan Aerial Forest Protection Service recorded 212 steppe fires in the northern part of the country, covering 47,000 hectares of land. These fires appear to have been the source of the smoke plumes observed over the Alaskan Arctic in April 2008 (Sukachev Institute, personal communication 2009).

Preliminary impressions of the human causes of vegetation burning in Russia and Kazakhstan suggest that the prevailing terms for classifying fires may be inadequate. While many fires are set for prescribed purposes, their "accidental" consequences often blur the divide between "agricultural" and "wild," "crop-residue" and "grassland," or "steppe" and "forest". Mitigating the effects of these fires on the Arctic will require more detailed knowledge of the ways in which human activities impact the landscape—not simply in the context of farming, but on the edges of cities, towns and smaller settlements where unmanaged land poses a heightened fire risk. Local authorities will need support

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and only go out into the countryside for parties on the weekends. They have lost their connection to nature."

from international institutions to increase public awareness and improve fire detection and control in these challenging zones.

Crop fires and economic development in China

China is a major source of Northern Hemisphere emissions from biomass burning. Within China, agricultural fires make up the largest portion of the total number of detected fires; 30-40% of all vegetation fires between 2001 and 2003 occurred in croplands, while 20-30% took place in forests, and 13-16% in savannas (Korontzi et al. 2006). Chinese producers regularly use fire as a tool in crop management, especially throughout the eastern half of the country. In northeastern China—the part of the country above 40 degrees latitude—rice, corn, soybean and wheat are harvested between August and October and planted in April. Farmers burn crop residue or "crop straw" in late winter and early spring to prepare their fields for sowing.

Over the past few decades, as China's agricultural economy has developed, the practice of field burning has spread. Prior to the 1970s, most peasant households relied on crop waste as a source of household fuel and animal fodder. But as crop yields improved through the 1980s, the total amount of crop straw produced began to outstrip domestic demand; farmers, eager to clear their fields quickly and cheaply, opted to burn excess waste rather than pay the cost of transport and storage (Cao et al. 2008).

Drawing on data from 2000-2003, researchers from the Chinese Academy of Meteorological Sciences in Beijing indentified crop waste burning in three primary agricultural areas: 1. Grain-producing regions with small population density, such as Jilin and Heilongjing in the northeast, that produce massive surplus straw. 2. More developed provinces, such as Zhejiang, Jiangsu, and Shanghai on China's eastern coast, where commercial energy has replaced agricultural waste as a fuel source, and 3. Energy-producing zones, in the interior of eastern China, like Shanxi and Shaanxi, where farmers have easy access to cheap energy sources, leaving a large crop waste surplus (Cao et al. 2008). Looking across these regions, the researchers found a strong positive correlation between farmers' income and the amount of crop straw burned—a pattern that will likely increase the pervasiveness of crop straw burning over time unless effective regulations are in place.

Although China's government officially prohibits open-field burning (and has even used satellite technology to monitor burning in rural areas), public compliance has been weak. To skirt the authorities, farmers frequently burn their fields at night, according to Shu Tao, a professor of environmental sciences at Peking University. Thick smoke from agricultural fires periodically forces provincial authorities to shut down highways. Calculations of emission factors from the burning of rice straw, wheat straw, and other crop residues indicate that nationwide, agricultural fires account for 11% of China's total black carbon output (Cao et al. 2008). Two of the top-emitting provinces—Heilongijiang and Jilin—fall in the northern most part of the country, above 40 degrees latitude, increasing the chances that their springtime black carbon contribution will affect the Arctic.

Thus far, Cao et al. (2008) have produced the only study on emissions from agricultural burning in China. But their work is a promising sign of an increased willingness among Chinese scientists to address this source of air pollution. Further research into the frequency and timing of crop fires in northeastern China—in combination with chemical transport data—will provide a better understanding of the potential climate impact of this type of biomass burning. Clearly, any successful plan to curb emissions from China's agricultural fires will have to include an alternate—economical—solution to the problem of surplus crop waste.

Agricultural fires in the U.S. and Canada—an underreported emissions source

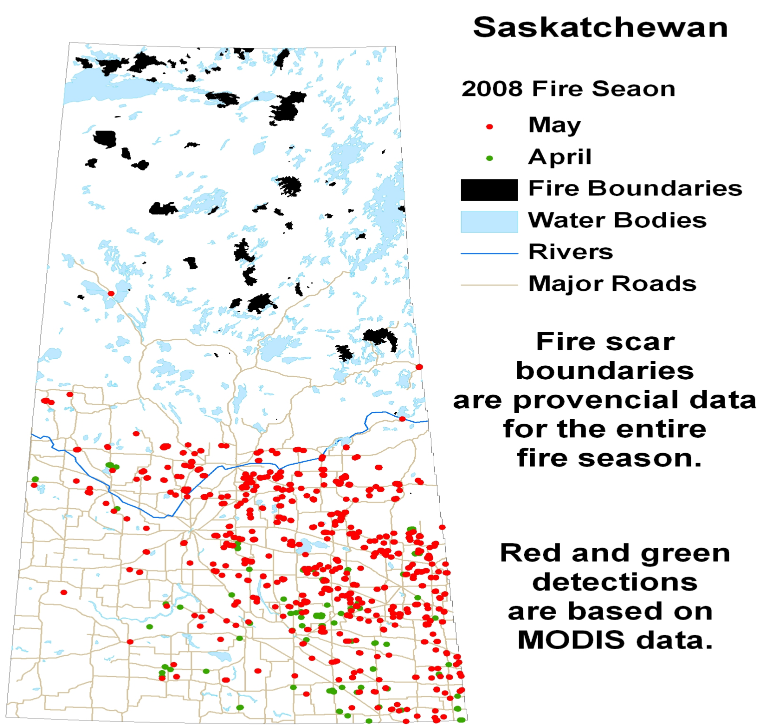
In the United States and Canada, governments have focused their fire management efforts primarily on the suppression of wildfires. These fires have increased in severity and frequency since the late 1980s. US agencies spend more than 1 billion dollars a year on fire control—much of it in response to extensive burning in the Southwest (USDA, 2006). Far less attention has been paid to other sources of biomass burning—such as agricultural fires—or to the possible climate effects of fire emissions.

According to Korontzi et al. (2006), croplands account for 30% of the total burned area in the contiguous United States. The bulk of agricultural burning takes place in the Southeastern states—Alabama, Georgia, and Florida—where industrial forestry is an economic mainstay. But seasonal crop residue fires also occur in the northern plains states—the Dakotas and northwest Minnesota, Iowa, Nebraska—and parts of Montana, which form a wheat belt extending north into the Canadian provinces of Saskatchewan and Alberta (Korontzi et al. 2006). Because much of this region lies above 40 degrees N latitude, it has the potential to affect Arctic pollution levels—particularly through the deposition of black carbon onto Greenland snow and ice.

Restrictions on agricultural fires in the US and Canada vary by state and province. In the US, many states require permits for open-field burning, and state officials post "no-burn" periods during exceptionally dry conditions. In Idaho, farmers must prove that "no viable alternative is available" before receiving permission to burn crop waste (House Bill no. 391, section 22-4803, 2003); in South Dakota, however, no permitting process exists for crop residue burning. Agricultural fires periodically damage property, as illustrated by a 2005 case in Helena, Montana that caught the attention of the associated press:

> …The spring burning season is a time when people burn debris and set fires to clear agricultural land, and when public lands agencies burn as part of their land-management plans. Farmers burn to reduce field stubble from previous crops or, in the case of grass producers, to clean fields and stimulate seed production, said Joel Clairmont, deputy state agriculture director. Thursday's fire in the Highwood area began with stubble burning in a grain field, Williams said. One of at least four Bitterroot fires Tuesday—all on one acre or less—charred two junked cars and the personal vehicle of a man who set a ditch blaze spread by afternoon wind (AP, March 3, 2005, reprinted in Firehouse.com).

In Saskatchewan, which contains 40% of Canada's farmland, there are no permitting requirements for agricultural burning. Provincial officials rely on farmers' judgment to avoid potentially hazardous burning conditions. In recent years, air quality concerns in cities and towns have encouraged farmers to observe wind patterns before setting fires and to burn "only when necessary." There is some evidence that fire frequency has been declining as farmers have acquired more effective chopping and spreading equipment (Wayne Gosslin, Saskatchewan Ministry of Agriculture, personal communication). A survey of 400 farmers in Saskatchewan found that flax straw—one of the toughest types of crop waste —was the most commonly burned crop residue. (65% of flax growers used fire to dispose of the straw, compared to 8% of cereal growers and 13% of canola growers.) A majority of farmers said they burned in fall (65%), while only 22% said they burned in spring (Saskatchewan Ministry of Agriculture survey, March 2008). MODIS records nevertheless show extensive fire activity in the crop and grasslands of southern Saskatchewan between January and June 2008.



Source: Amber Soja, NASA, 2008.

Lack of adequate fire recording has so far hampered efforts to determine the black carbon impact of agricultural burning in the US and Canada. Federal fire statistics in the US have little spatial accuracy, tend to be aggregated at the county level, and may exclude fires outside of public lands (Brown et al. 2002, Schmidt et al. 2002, cited in Hawbaker 2009, unpublished manuscript). As Soja et al. (2009) point out: the US government does not keep a standard database of fire events or area burned for any year.[7] Canadian fire agencies similarly maintain records only of large forest fires. Researchers are currently working in both countries to incorporate satellite technology as a means of tracking small fire occurrences on agricultural and other non-federal lands. This is a crucial first step toward calculating annual national emissions totals from biomass burning (Hawbaker, personal communication 2009; Soja et al. 2009).

Conclusion: Finding regional solutions to springtime black carbon emissions

Taken individually, agricultural fires leave a relatively small print on atmospheric pollution levels, especially when compared to large boreal forest fires or fossil fuel emissions. But as part of a seasonal pattern of biomass burning, these anthropogenic fires constitute a substantial portion of short-lived pollutants that affect the Arctic. In regions where land-use changes have led to high rates of rural abandonment and re-vegetation, agriculture-related burning often ignites swaths of adjacent grassland and even threatens peripheral forest. When set in spring under the right weather conditions, these blazes send soot into the Arctic that has the potential to speed the pace of snowmelt and trigger further warming effects. In addition, while not covered here, emissions from these fires can increase Arctic concentrations of tropospheric ozone—another short-lived pollutant.

Any attempt to slow the rate of Arctic climate change must address the problem of black carbon transport. Agricultural fires present a clear target for mitigation. At a minimum, Charles Zender, a professor of earth system science at UC Irvine argues, "shifting prescribed burning to seasons other than spring could help clean and brighten the Arctic." Yet, enforcement of global fire restrictions is likely to prove challenging, given the widely variable circumstances under which agricultural burning takes place

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[7] For instance, to estimate forest and wildfire emissions for the 1999 emissions year, the EPA used fire activity data for the years 1985-1998 obtained from the U.S. Department of Interior and the USFS for Non-Grand Canyon States. After the emissions estimates were produced, they were often distributed from an aggregated state level to a county level using data from a prior year(s). This often led to large errors and inaccuracies when comparing where emissions were shown to occur and where actual biomass burning occurred. Recently, in a large part as a result of this work, the EPA had begun to include satellite data in the National Emissions Inventory (Soja et al. 2009)

around the world. International efforts to curb biomass-burning emissions must begin with regional solutions that take account of local realities—the ecological conditions, farmers' motivations, and governmental challenges that contribute to the pervasiveness of intentional and accidental fires.

In Russia and the former Soviet republics, the issue of agricultural burning is inseparable from the broader crisis of fire management. The enormous area of land, extending from Eastern Europe across Siberia, accounts for the large majority of northern hemisphere emissions from crop-waste burning, yet there is virtually no in-country accounting of these fires. MODIS satellite data tell a story that is difficult to verify on the ground. Many governments appear to lack both the will and the funds to address the causes of burning practices in rural areas. Currently the Global Fire Monitoring Center—a program under the United Nations' International Strategy for Disaster Reduction (UN-ISDR)—is taking steps to improve national fire management in Russia, Kazakhstan, and many Eastern and Southeastern European countries. The project promotes cross-border agreements on wildfire control and educates local communities about the "proper application of land-use fires" as well as the best methods for preventing and suppressing wildfires. (See: http://www.fire.uni-freiburg.de/Manag/CBiM.htm). Increased public awareness of the impact of careless burning on local ecology, respiratory health and climate will help pave the way for effective regulations on agricultural fires—and ideally a springtime ban. Supporting the educational and diplomatic efforts of the Global Fire Monitoring Center should thus be a priority of the United Nations Framework Convention on Climate Change (UNFCCC) going forward.

In China, prohibitions on agricultural fires have proved ineffective in the face of strong economic incentives for crop straw burning. In order to reduce China's springtime black carbon emissions, farmers need a viable alternative method of crop waste removal. Conventional plowing has the advantage of returning more nitrogen and other nutrients to the soil, but it does not dispose of pests; moreover, from a climate perspective, tilling fields has the disadvantage of releasing additional stores of CO_2 into the atmosphere. Modern equipment for chopping and spreading crop straw is also unlikely to be cost effective for the majority of Chinese producers. Local Chinese efforts to improve the uses of bio-energy could be part of the solution; "crop straw gasification" appliances have recently become available in northeastern China for home heating use (see: www.gasifiers.bioenergylists.org). These kinds of devices—if popular with consumers and effective at disposing of crop residue with fewer emissions—could create a needed market for surplus crop waste and decrease incentives for burning.

Addressing North America's contribution to Arctic black carbon in spring will require greater documentation of agricultural fires in Canada and the northern Great Plains states. Preliminary investigation suggests that fall is the preferred burning season for Canadian and northern plains farmers, but satellites show that burning also occurs in spring. Already many states and provinces view agricultural fires as the choice of last resort because of their effects on local air quality and highway visibility. Making the case that these fires are accelerating the onset of spring melt in the Arctic should make choosing alternatives to spring burning more imperative.

One promising mitigation approach, with global potential, may lie in the development of new technologies aimed at sequestering carbon from burned crop waste and then returning the charred biomass to the soil as fertilizer. Biochar offers a possible opportunity to capture the energy value of crop residues and return carbon-rich char to the soil, instead of uncombusted emissions, thus providing a source of both carbon storage and soil improvement through the addition of a material rich in organic matter. Research is currently underway to develop portable, on-farm pyrolysis systems capable of converting agricultural residues to biochar (see: www.mistra.org).

Every spring, the Arctic becomes more vulnerable to the inflow of short-lived pollutants. As Charles Zender, points out: "Arctic snow and ice currently exist under a blanket of man-made greenhouse gases that keeps them significantly warmer and more susceptible to pollution-induced melting than at any time in recent human history." An immediate reduction in black carbon emissions will slow warming more than will a delayed response. Black carbon will have a smaller in a future Arctic with less snow and ice.

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