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Chapter 1

Impacts of Vegetation Fire Emissions on the Environment, Human Health, and Security: A Global Perspective

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Abstract

Air pollution generated by vegetation fire smoke (VFS) is a phenomenon that has influenced the global environment in prehistoric and historic time scales. Although historic evidence of the impacts of VFS on societies is scarce, there are indications that VFS has been a factor that influenced society significantly since the Middle Ages. In recent decades, increasing application of fire as a tool for land-use change has resulted in more frequent occurrence of extended fire and smoke episodes with consequences on human health and security. Some of these events have been associated with droughts that are attributed to inter-annual climate variability or possible consequences of regional climate change. In metropolitan or industrial areas, the impacts of VFS may be coupled with the emission burden from fossil fuel burning and other technogenic sources, resulting in increasing adverse affects on the human population. We review the character, magnitude, and role of pyrogenic gaseous and particle emissions on the composition and functioning of the global atmosphere, human health, and security. Special emphasis is given on radioactive emissions generated by fires burning in peatlands and on terrain contaminated by radionuclides. The transboundary effects of VFS pollution are a driving argument for developing international policies to address the underlying causes for avoiding excessive fire application, and to establish sound fire and smoke management practices and protocols of cooperation in wildland fire management at an international level.

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1.1. Introduction

1.1.1. Vegetation fire–smoke pollution: Prehistoric and historic evidence

Prehistoric occurrence of fire smoke emissions and the deposition of fire–smoke aerosol in lakes and on ice have been documented by a large number of sediment and ice core studies, which provide important sources for reconstruction of fire activities (Clark et al., 1997). In addition to biogenic, marine, and soil-dust particles, the smoke from vegetation fires has determined the composition and functioning of the natural global atmosphere before the expansion of human populations and the industrial age (Fig. 1.1; Andreae, 2007).

In the history of land-use phenomena and problems, vegetation fire smoke (VFS) has been documented in a few cases. One example is the smoke pollution generated by land-use fires and land-use change in northern Germany since the 16th century. At that time, large uncultivated bogs and swamps dominated the region. With population growth, people were forced to enlarge the area under production and started to cultivate these areas by burning the bogs (Goldammer, 1998).

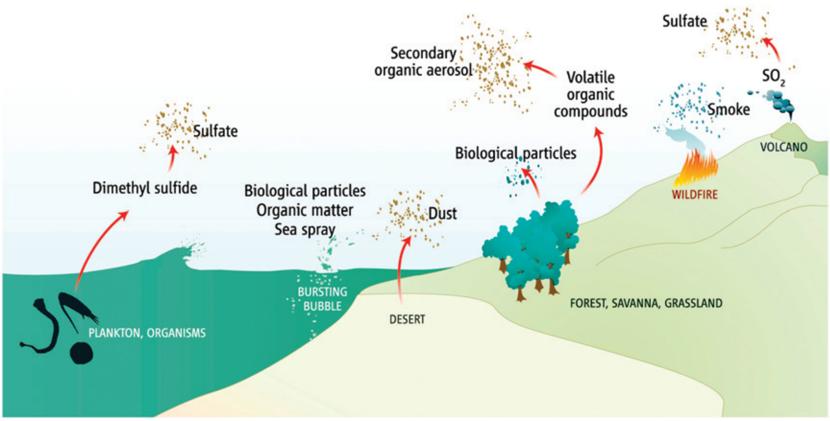


Figure 1.1. Sources of aerosol particles to the natural atmosphere: Primary particles—such as sea spray, soil dust, smoke from wildfires, and biological particles including pollen, microbes, and plant debris—are emitted directly into the atmosphere. Secondary particles are formed in the atmosphere from gaseous precursors; for example, sulfates are formed from biogenic dimethyl sulfide and volcanic sulfur dioxide (SO_2), as well as, secondary organic aerosol from biogenic volatile organic compounds. (Reprinted with the permission of Andreae 2007 and the American Association for the Advancement of Science (AAAS). Copyright: AAAS, 2007.)

Burning of bogs began usually in mid-May and ended in June. The drying of the organic material and the heat caused the break up of the normally barely accessible plant nutrients of the bog, enabling cultivation of oats and buckwheat on the freshly burned fields without fertilization. The burning of bogs was first noted in the year 1583. Smoke pollution from bog burning (Fig. 1.2) seemed to have an oppressive effect in northwestern Germany, even in areas far away. This effect, the "smell of burning" was known under the term "High Smoke". First historic evidence of an extended regional European fire–smoke episode dates back to the end of the 17th century. In 1657, the bog burnings began on May 6 in Northern Friesland, carried by strong easterly winds. On the next day, the smoke reached Utrecht (Netherlands), and a little bit later had changed direction, passing Leeuwarden towards Den Helder, and reaching the sea on May 15. There, the wind changed northwest and drove the bog smoke back, so that on May 16 it had reached Utrecht and Nijmwegen again. At the same time, the smoke was also noticed in Hanover, Münster, Köln, Bonn, and Frankfurt. On May 17, 1657, the smoke reached Vienna, on May 18 Dresden, and on May 19 Kraków (Poland).

Figure 1.2. Moor burning in Friesland (Frisia) around 1900. Sometimes smoke from these land-use fires covered large areas of Europe. (*Source*: Archive, Fire Ecology Research Group/Global Fire Monitoring Center.)

Other historic evidence is provided by the description of a large-scale fire–smoke pollution in Russia in 1915 (Shostakovich, 1925). Reports indicate the effects of a 50-day fire episode between June and August 1915, during which more than 140,000 km^2 of forest lands were affected by fire between Angara River and Nijnya Tunguska. Smoke pollution was reported on a total land area of about 6 million km^2 with extreme pollution, resulting in visibility of less than 20 m on more than 1.8 million km^2.

1.1.2. Contemporary trends in vegetation fire–smoke pollution

As a consequence of demographic developments and increasing pressure on vegetation resources in many developing countries, the application of fire as a land-clearing tool in large-scale land-use change projects, increased rapidly over the past three to four decades. In addition to traditional land clearing by small landholders shifting cultivation (slash-and-burn agriculture), the establishment of pastures and sugar cane plantations in Brazil, forest clearing for the establishment of palm oil plantations, or other cash crops in Southeast Asia, and other tropical regions involves massive burning of vegetation. During droughts, such as the dry spells associated with the El Niño-Southern Oscillation phenomenon, land-use fires also escape to large uncontrolled wildfires, reinforcing the fire–smoke burden at regional scales.

Other regions that are undergoing urbanization are experiencing an abandonment of the rural space. The rural exodus often results in an increase of wildfire hazard, due to decreasing land cultivation and utilization of vegetation resources. Increased fuel loads (combustible materials) are resulting in more severe and often uncontrollable fires. Portugal is one of the most impressive examples where land abandonment—coupled with the establishment of highly flammable eucalypt and pine plantations—has resulted in extended fire and smoke pollution episodes (Varela, 2006).

Other regions of the world are suffering an unhealthy combination of socioeconomic, political, and environmental drivers of ecosystem impoverishment and land degradation. In countries undergoing political and economic transition in Eurasia the institutional and political capabilities to practice efficient forest fire management have declined to an extent that fires are becoming almost uncontrollable. This is especially the case in the central Asian region (Goldammer, 2006a), where regional droughts associated with illegal forestry activities, arson, and negligence have resulted to extended severe fire episodes with smoke pollution affecting neighboring countries and long-range smoke transport in the Northern Hemisphere.

1.2. Fundamentals

1.2.1. VFS formation

Generally, vegetation fire can be considered as a four-phase process consisting of the pre-ignition, flaming, smoldering, and glowing phases. In the first phase (pre-ignition), heat from an ignition source or the flaming front evaporates water and the low molecular weight volatiles from the fuel and the process of pyrolysis begins. In the second phase (flaming), combustion of the pyrolysis products (gases and vapors) with air takes place. Flaming occurs if these products are heated to the ignition point (325–350°C) (US NWCG, 2001). The heat from the flaming reaction speeds the rate of pyrolysis and produces greater quantities of combustible gases, which also oxidize, causing increased flaming. The third phase (smoldering) is a very smoky process occurring after the active flaming front has passed. Combustible gases are still produced by the process of pyrolysis, but the rate of release and the temperatures are not high enough to maintain flaming combustion. Smoldering generally occurs in fuelbeds with fine packed fuels and limited oxygen flow. In the fourth phase (glowing), most of the volatile gases have been burned, and oxygen comes into direct contact with the surface of the charred fuel. As the fuel oxidizes, it burns with a characteristic glow, until the temperature is reduced so much that combustion cannot be continued, or until all combustible material is consumed (Johnson, 1999).

A vegetation fire is the result of interaction of three components—fuel, oxygen, and heat of combustion (fire triangle). The fuel is in principle the forest, or more generally, the vegetation. However, other types of fuels and/or materials may contribute to the VFS formation and composition during the flame-front expansion (Statheropoulos & Karma, 2007).

Vegetation fuels have specific characteristics, such as fuel moisture and fuel temperature, which contribute to the combustion process (see this volume, for a full discussion of weather and climatic influences on fire and combustion). Generally, vegetation fuel with high moisture content, such as big branches or tree trunks, produces water vapor that lowers the temperature of combustion and hence favors smoldering. The specific characteristics of the fuel, such as the amount and size burned, contribute mainly to the quantity of the smoke produced.

The oxygen-(O_2)-to-fuel ratio can be affected by wind speed and direction and also vegetation characteristics, such as vegetation density (packing ratio), shape, and arrangement (structure). The O_2-to-fuel ratio mainly contributes to the type of components in the VFS. For example, evolution of carbon monoxide (CO) and fine particles dominates in incomplete combustion (limited oxygen flow, smoldering phase), whereas in complete combustion (oxygen flow, flaming phase) the emission of carbon dioxide (CO_2) and H_2O is favored. However, O_2 flow also affects the amounts of smoke produced: the amount of particulate emissions generated per mass of fuel consumed during the smoldering phase is more than double that of the flaming phase (US NWCG, 2001).

The heat component of the fire triangle can contribute to the smoke components produced. An indicative example is that organic degradation of pine needles has been found to commence at 200–250°C, while maximum evolution rate of organic volatiles was found to occur in the temperature range 350–450°C (Statheropoulos et al., 1997); according to another source, peak production of combustible products was found to occur when the fuels were heated in the range of 300°C (Johnson, 1999). Recently, airborne measurement of sensible heat and carbon fluxes in fire plumes were combined with remote measurements of flame properties to provide consistent remote-sensing-based estimators of these fluxes. These estimators provide a mean to determine rates of fuel consumption and carbon emission to the atmosphere by wildland fires as required for assessments of fire impacts on regional air pollution or global emissions of greenhouse gases (Riggan et al., 2004).

1.2.2. VFS chemical composition

Generally, VFS is considered an aerosol, which is defined as a colloidal system in which the dispersed phase is composed of either solid or liquid particles in gas, usually air (Johnson, 1999).

VFS, basically, consists of water vapor, permanent gases, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and particles (Andreae and Merlet, 2001). Permanent gases include CO_2, CO, nitrogen oxides (NO_x) (Muraleedharan et al., 2000; Radojevic, 2003). Sulfur oxides (SO_x) and ammonia (NH_3) have also been reported. SO_x are usually produced in small quantities, because in general vegetation fuel sulfur content is low (Ward & Smith, 2001). Concentrations of SO_2 identified in Brunei Darussalam during the 1998 smoke-haze episode were below World Health Organization (WHO) guidelines levels of 100–150 $\mu g m^{-3}$ (Radojevic, 2003). However, high amounts of sulfur-based compounds are created when sulfur-rich vegetation or soil are burned; for instance, significant quantities of SO_2 and hydrogen sulfide (H_2S) were produced by forest fires burning in Yellowstone National Park (Reh & Deitchman, 1992). NH_3 has been measured in forest and savannah fires (Hegg et al., 1988, 1990; Lacaux et al., 1995; Koppmann et al., 2005). However, the emission ratio of NH_3 relative to CO_2 has generally been found low; NH_3 is primarily emitted during the smoldering rather than during the flaming phase of combustion (Koppmann et al., 2005).

Methane (CH_4) and various VOCs have been found in VFS (Heil & Goldammer, 2001; Miranda, 2004; Ward, 1999). Hydrocarbons identified were aliphatic, such as alkanes, alkenes, and alkynes. Representative compounds included ethane, heptane, decane, propene, 1-nonene, 1-undecene, and acetylene (McDonald et al., 2000; Shauer et al., 2001; Statheropoulos & Karma, 2007; Ward & Smith, 2001). Additionally, aromatic hydrocarbons, such as benzene and alkylbenzenes have been found; for example, toluene, xylene, and ethyl-benzene (Muraleedharan et al., 2000; Reh & Deitchman, 1992; Statheropoulos & Karma, 2007). Moreover, VOC mixtures included the following oxygenated compounds: alcohols (phenol, m-cresol, p-cresol, guaiacol) (McDonald et al., 2000; Shauer et al., 2001; Statheropoulos & Karma, 2007; Ward & Smith, 2001), aldehydes (formaldehyde, acetaldehyde, furfural, acrolein, crotonaldehyde, benzaldehyde) (Kelly, 1992; Reh & Deitchman, 1992; Reinhardt & Ottmar, 2004; Shauer et al., 2001; Statheropoulos & Karma, 2007), ketones (acetone, 2-butanone) (McDonald et al., 2000; Statheropoulos & Karma, 2007), furans (benzofuran), carboxylic acids (acetic acid), and esters (benzoic acid, methyl ester) (McDonald et al., 2000; Muraleedharan et al., 2000; Reh & Deitchman 1992; Statheropoulos & Karma, 2007; Ward & Smith, 2001). Also, it has been shown that during fireplace pine wood combustion experiments and in a pine forest fire incident, chloro-methane was detected in the smoke produced (McDonald et al., 2000; Statheropoulos & Karma, 2007). Chloro-methane has been identified as the most abundant halogenated hydrocarbon emitted during biomass burning, mainly consisting of dead and living vegetation (e.g., savannahs, fuel wood, agricultural residues; (Andreae et al., 1996; Koppmann et al., 2005; Urbanski et al., this volume). SVOCs found in the VFS were polyaromatic hydrocarbons (PAHs), such as benzo (a) pyrene (Booze et al., 2004; Kelly, 1992; Muraleedharan et al., 2000; Reh & Deitchman, 1992; Ward, 1999) (also see Urbanski et al., this volume).

Generally, VFS contains particulate matter (PM) (Reid et al., 2005). Particles can be coarse, with diameter up to 10 μm (PM_{10}), fine with diameter up to 2.5 μm ($PM_{2.5}$), or ultrafine with diameter smaller than 0.1 μm (Sandström et al., 2005). The PM can be primarily released to the atmosphere due to combustion or can be formed through physical or chemical transformations (molecular agglomeration of supersaturated vapors, nucleation). Primary particles can be elemental carbon or organic carbon particles. Inorganic or elemental carbon, also known as graphitic or black carbon (soot), is a product of the incomplete combustion of carbon-based materials and fuels (CEPA, 1999). Organic carbon can also be produced via secondary gas-to-particle conversion processes. Condensation of hot vapors (VOCs, SVOCs) during combustion processes (tars) and also nucleation of atmospheric species result in formation of new particles, usually below 0.1 μm in diameter. Generally, low-volatility products either nucleate or condense on the surfaces of pre-existing particles, yielding particles in the size range 0.1–1.0 μm (CEPA, 1999).

Trace elements can also be contained in particles produced from forest fires, such as sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), manganese (Mn), iron (Fe), zinc (Zn), vanadium (V), lead (Pb), copper (Cu), nickel (Ni), bromine (Br), and chromium (Cr) (Muraleedharan et al., 2000; Radojevic, 2003; Reh & Deitchman, 1992; Ward & Smith, 2001). These species are usually absorbed on the surface of fine particles.

Particles, as PM_{10} and $PM_{2.5}$ have been measured in different forest fires, such as during the Gestosa experimental fires in Portugal (Miranda et al., 2005), during the 1997 haze episode in Southeast Asia (Muraleedharan et al., 2000; Ward, 1999), in the U.S. state of Montana 2000 wildfire season (Ward & Smith, 2001), in Korea during May 2003 (aerosol impact due to forest fires in the Russian Federation) (Lee et al., 2005), and in a forest fire in Greece (Statheropoulos & Karma, 2007).

However, VFS can exist as a more complicated mixture depending on the flame-front pathway. If a vegetation fire is in the interface of an urban area, it is possible the flame-front will co-burn fuels other than vegetation, such as wastes. In this case, synthesis of VFS can be the additive or synergistic result of all the possible emission products due to the pyrolysis and combustion of the vegetation and the wastes; significant quantities of hazardous components, such as dioxines (polychlorinated dibenzo-p-dioxines/polychlorinated dibenzo-furans PCDDs/PCDFs), can also be contained in the resultant VFS. Additionally, when vegetation fires pass over rural fields or rural/urban constructions, then wood, plastics, or fertilizers can also be burned and materials, such as pulverized glass, cement, dust, asbestos, plaster, or other chemical compounds can be contained in the smoke produced. Various scenarios of forest flame-front pathways and the possible related VFS chemical composition have been integrated in a road map for air-quality assessment (Statheropoulos & Karma, 2007).

It has to be noted that radioactive species can, occasionally be found in VFS. Their origin can be from vegetation fuel radioactively contaminated, such as a forest in the site of the Chernobyl Nuclear Power Plant Exclusion Zone (Dusha-Gudym, 2005; Poyarkov, 2006). It has been reported that in 1992, severe wildfires that burned in the Gomel Region (Belarus) spread into the 30 km radius zone of the Chernobyl Power Plant and the level of radioactive cesium in aerosols was increased 10 times within the 30 km zone (Dusha-Gudym, 2005; WHO/UNEP/WMO, 1999) (see Section 1.4.1 of this chapter and Hao et al., this volume).

1.2.3. VFS components concentration and exposure limits

During vegetation fires, high peak concentrations of VFS components can be observed, especially near the flame-front. Table 1.1 presents mean concentrations of VFS components measured in "smoky" conditions in the field (sampling duration 20–30 min) that have been reported in the literature (Miranda et al., 2005; Pinto & Grant, 1999; Reinhardt et al., 2000; Statheropoulos & Karma, 2007), together with the short-term limits recommended by the National Institute for Occupational Safety and Health (NIOSH). In general, exposure limits given by various health organizations that are presented in this chapter for comparison should be considered as indicative and not as references because they refer to indoor occupational exposure.

Concentrations of PM_{10} as high as 47,600 $\mu g\,m^{-3}$ have been found (Reh & Deitchman, 1992), whereas the exposure limit for 24 h given by the American Conference of Governmental Industrial Hygienists (ACGIH) is 150 $\mu g\,m^{-3}$. Moreover, $PM_{2.5}$ levels measured in the field,

Table 1.1. Mean concentrations measured in smoky conditions in the field and short-term occupational exposure limits (STELs)

Compound	Concentration	Short-term exposure limits (NIOSH, 1997)
CO[a]	54 ppm	200 ppm
CO_2[b]	350 ppm	30,000 ppm
Benzene[b]	0.22 ppm	1 ppm
Toluene[b]	0.12 ppm	150 ppm
Xylene[b]	0.08 ppm	150 ppm
Acroleine[a]	0.071 ppm	0.3 ppm
Formaldehyde[a]	0.468 ppm	0.1 ppm
BenzoPyrene (BaP)[c]	7.1 $n\,gm^{-3}$	—
$PM_{2.5}$[a,d]	[a,b]7000 $\mu\,gm^{-3}$, [d]2300 $\mu\,gm^{-3}$	[e]65 $\mu\,gm^{-3}$ (24 h)

[a]Reinhardt et al. (2000).
[b]Statheropoulos and Karma (2007).
[c]Pinto and Grant (1999).
[d]Miranda et al. (2005).
[e]American Conference of Governmental Industrial Hygienists (ACGIH).

at a distance of approximately 70 m from the flame-front, were estimated to be 49,500 $\mu g\,m^{-3}$ (Statheropoulos & Karma, 2007); the respective ACGHI 24 h limit is 65 $\mu g\,m^{-3}$.

Airborne measurements of fire emissions at a distance of 200–1000 m above the flame-front have shown that CO concentration ranged between 100–600 ppb with an average and standard deviation of 310 ± 10 ppb (Yokelson et al., 2007).

1.3. VFS emissions from various vegetation types

National statistical databases on the spatiotemporal extent of wildland fires—numbers and size of fires occurring in forests, other wooded lands, and other lands—are not only important for fire management planning but also for environmental, economic, and humanitarian impact assessments. In the majority of the countries of the world, the data collected by agencies on the ground or by aerial monitoring do not reflect the full extent of wildland fires. In most countries the forestry agencies or other services are collecting data only for the protected forests and other protected vegetation under their respective jurisdiction. Only in a few countries, data of grassland, steppe, and peat bog fires are entering the statistical databases. The fire statistical data provided by the recent survey in the regions of the Global Wildland Fire Network within the Global Forest Resources Assessment 2005 reflect this general situation and therefore do not provide a complete picture (FAO, 2007).

Other data sets on spatial and temporal occurrence of vegetation fires have been produced, based on various spaceborne sensors, such as the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), Medium-Resolution Imaging Spectrometer (MERIS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Satellite Pour l'Observation de la Terre or Earth-observing Satellite (SPOT) Vegetation instruments. These data sets include all vegetation types affected by fire. Active fires and area burned recorded from space include both the ecologically benign fires burning in fire-dependent or adapted ecosystems and the economically and environmentally detrimental fires burning in fire-sensitive systems. Thus, these satellite-derived data cannot be compared directly with the conventionally collected data of the forest agencies, which are generally restricted to wildfires occurring in production or protected forests.

One of the global satellite-derived assessments of land areas affected by fire in the year 2000 was conducted by the Global Vegetation

Monitoring (GVM) unit of the Joint Research Center (JRC), in partnership with other six institutions, using the medium-resolution (1 km) satellite imagery provided by the SPOT-Vegetation system (JRC, 2002). According to the data set, the global vegetated area affected by fire in the year 2000 was 350 million ha (details on the area burned by country can be downloaded at the JRC Web site (JRC, 2002)).

Based on such global satellite-derived data sets and/or published statistics and models, a number of studies have been conducted to estimate total global gaseous and aerosol emissions from vegetation fires, such as the most recent Global Wildland Fire Emission Model (GWEM) (Hoelzemann et al., 2004).

Table 1.2 provides an overview of global emission of selected species annually emitted from vegetation fires in the late 1990s, based on emission factors as summarized by Andreae (2004) (for more information on chemical emissions from different fuel types, see Ottmar et al., this volume).

1.4. Smoke dispersion

VFS produced by large vegetation fires is usually transported many kilometres away from the flame-front. Usually, fine particles can be transported to long distances (cross border transfer). Table 1.3 presents some of the VFS pollutants and their transfer through the environment are presented (Brauer, 1999). According to Nakajima et al. (1999), during the 1997 episode in Southeast Asia, the smoke-haze layer covered an area up to 10 million km^2. Moreover, during 2002, the Canadian forest fires in a province of Quebec affected the PM levels of the city of Baltimore in the United States, which is located hundreds of kilometres from the source (Sapkota et al., 2005). Fires in Canada were also found to cause high concentrations of CO and O_3 over a period of 2 weeks in the southeastern and eastern coastal United States during the summer of 1995 (Wotawa & Trainer, 2000).

1.4.1. Transport of radionuclides in VFS

As a result of the failure of the Chernobyl nuclear power plant, a total of 6 million ha of forest lands were polluted by radionuclides. The most polluted forest area covers over 2 million ha in the Gomel and Mogilev regions of Belarus, the Kiev region of Ukraine, and the Bryansk region of the Russian Federation. The main contaminator is caesium-137 (^{137}Cs); in the core zones of contamination, strontium-90 (^{90}Sr) and

Table 1.2. Global annual emission of selected chemical species in the late 1990s (in mass of species per year; $Tg\,a^{-1}$)

Compound[a]	Savanna and grassland	Tropical forest	Extra-tropical forests	Biofuel burning	Charcoal making and burning	Agricultural residues	Total pyrogenic	Fossil fuel burning
Tg dm burned[b]	3160	1330	640	2663	196	1190	9200	—
CO_2	5096	2101	1004	4128	169	1802	14,300	23,100
CO	206	139	68	206	19	110	750	650
CH_4	7.4	9.0	3.0	16.2	1.9	3.2	41	110
NMHC	10.7	10.8	3.6	19.3	0.4	7.6	53	200
Methanol	3.8	2.6	1.3	3.9	0.16	2.1	13.8	—
Formaldehyde	1.1	1.8	1.4	0.4	0.10	1.4	6.3	—
Acetaldehyde	1.6	0.86	0.32	0.36	0.05	0.68	3.9	—
Acetone	1.4	0.83	0.35	0.06	0.05	0.65	3.3	—
Acetonitrile	0.33	0.24	0.12	0.48	0.01	0.21	1.4	—
Formic acid	2.1	1.4	1.8	0.35	0.11	0.3	6.0	—
Acetic acid	4.2	2.8	2.5	2.4	0.30	1.0	13.1	—
NO_x (as NO)	12.2	2.2	1.9	2.9	0.16	3.0	22.3	45
N_2O	0.67	0.27	0.17	0.16	0.01	0.08	1.4	2.0
NH_3	3.4	1.7	0.88	3.5	0.06	1.5	11.0	0.4
SO_2	1.1	0.76	0.64	0.73	0.015	0.48	3.7	228

COS	0.05	0.05	0.02	0.11	0.01	0.07	0.31	—
CH_3Cl	0.24	0.10	0.03	0.14	0.0005	0.28	0.80	—
CH_3Br	0.006	0.010	0.002	0.008	0.00011	0.004	0.031	—
$PM_{2.5}$	16.1	12.0	8.3	19.1	0.34	4.6	60	—
TPM	26.2	11.3	11.3	25.1	1.1	15.5	91	—
TC	11.7	8.7	5.3	13.8	0.24	4.8	45	27
OC	10.6	7.0	5.8	10.5	0.18	3.9	38	20
BC	1.5	0.88	0.36	1.6	0.06	0.82	5.2	6.6
K	1.09	0.39	0.16	0.14	0.02	0.33	2.1	—
CN	1.1E+28	4.5E+27	2.2E+27	9.1E+27	1.3E+26	4.0E+27	3.1E+28	—
CCN (1% SS)	6.3E+27	2.7E+27	1.7E+27	5.3E+27	7.6E+25	2.4E+27	1.8E+28	—
$N_{(>0.12\,\mu m\ diameter)}$	3.7E+27	1.3E+27	6.4E+26	2.7E+27	3.8E+25	1.2E+27	9.6E+27	—

[a] Abbreviations: NMHC, non-methane hydrocarbons; N_2O, nitrous oxide; COS, carbonyl sulfide; CH_3Cl, methyl chloride; CH_3Br, methyl bromide; $PM_{2.5}$, particulate matter < 2.5 µm diameter; TPM, total particulate matter; TC, total carbon; OC, organic carbon; BC, black carbon; CN, condensation nuclei; CCN, cloud condensation nuclei at 1% supersaturation; $N_{(>0.12\,\mu m\ diameter)}$: particles > 0.12 µm diameter; $E = 10^{20}$.
[b] 1 Tg, 1 million metric tons; dm, dry matter.

Table 1.3. Indicative VFS compounds and how they are transported from the source (Brauer, 1999)

Compound	Example	Notes
Permanent gases	CO, CO_2	Transported over distances[a]
	O_3	Only present downwind of fire-transported over distances
	NO_2	Reactive concentrations decrease with distance from fire
Hydrocarbons	Benzene	Some transport, and react to form organic aerosols
Particles	PM_{10}	Coarse particles are not transported and contain mostly soil and ash
	$PM_{2.5}$	Fine particles transported over long distances

[a]CO measured in the smoke plume of a tropical forest fire was transported to a distance greater than 500 km (Yokelson et al., 2007).

plutonium-239 (^{239}Pu) are found in high concentrations. This region constitutes the largest area in the world with the highest contamination by radionuclides and is located in a fire-prone forest environment in the center of Europe.

Every year, hundreds of wildfires are occurring in the contaminated forests, peatlands, and former agricultural sites. Between 1993 and 2001 a total of 770 wildfires in the closed zone of Ukraine affected 2482 ha. In the period 1993–2000, 186 wildfires occurred in the closed zone of Belarus and affected an area of 3136 ha including 1458 ha of forest. In Ukraine in 2002 alone, a total area of 98,000 ha of wildland was burned in the contaminated region of Polissya.

Under average dry conditions, the surface fuels contaminated by radionuclides—the grass layer and the surface layer of peatlands—are consumed by fire. Most critical is the situation in peat layers, where the radionuclides are deposited. The long-range transport of radionuclides lifted in the smoke plumes of wildfires and their fallout on large areas were investigated in detail in 1992. Radioactive smoke plumes, containing caesium-137, were monitored several hundred kilometres downwind from the sites where fires occurred in May and August 1992 (Dusha-Gudym, 2005).

This risk of radioactive contamination has not decreased substantially and is particularly threatening the population living in the immediate environment of the accident site (4.5 million people). Radioactive emissions are also a high risk for firefighters. In addition, populations are affected by radioactive smoke particles transported over long distances (Dusha-Gudym, 2005; Poyarkov, 2006).

A similar situation is found in Kazakhstan. At the Semipalatinsk Nuclear Weapons Test Site, more than 450 nuclear tests, including about

100 atmospheric tests, were conducted for a period of 40 years between 1949 and 1989. Radioactive contamination is highest in Eastern Kazakhstan, including the fire-prone pine forests along the Irtysh River at the border to the Russian Federation (Gorno-Altay). A recent report reveals that radioactive emissions from fires burning in central Asia in 2003 were recorded in Canada (Wotawa et al., 2006).

1.4.2. Remote-sensing methods to monitor VFS

There are satellite systems with aerosol detection capability. The National Oceanic and Atmospheric Administrationolar Operational Environmental Satellite (NOAA POES) AVHRR and the NASA MODIS are such examples (Fig. 1.3a and b). The NASA Stratospheric Aerosol and Gas

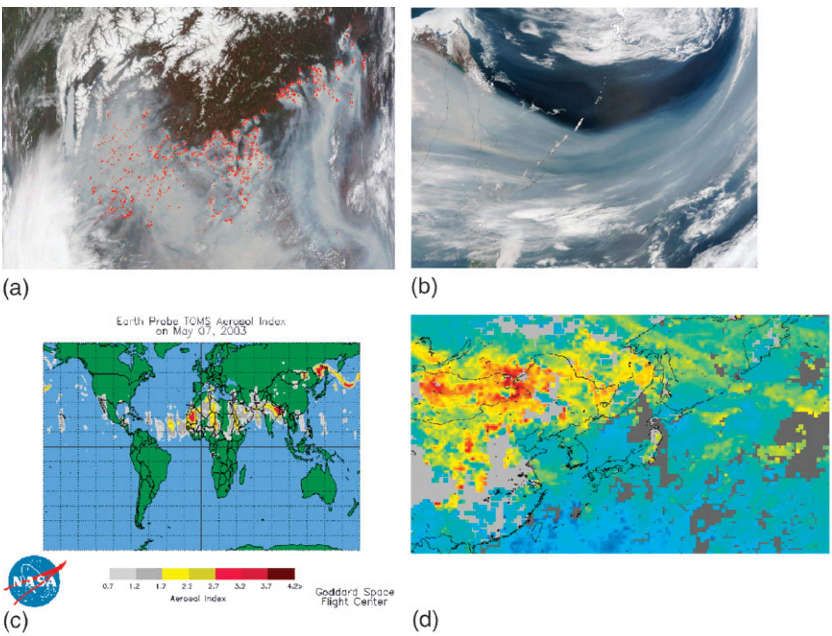


Figure 1.3. (a) Active fires in the Transbaikal Region (Russian Provinces Chita and Buryatia) depicted by the MODIS instrument on Terra, May 8, 2003 (courtesy: NASA). (b) Smoke plume from fires burning in the Transbaikal Region on May 8, 2003, stretching to Sakhalin and northern Japan (MODIS). (c) Smoke plume from fires burning in the Transbaikal Region stretching to Sakhalin and northern Japan (MODIS) on May 7, 2003 as depicted by NASA TOMS. (d) May 3–8, 2003, carbon monoxide concentration originated by VFS in the Transbaikal Region depicted by the MOPITT instrument on the Terra satellite (courtesy: NASA).

Experiment (SAGE) provides vertical resolution. The Total Ozone Mapping Spectrometer (TOMS) depicts aerosols at coarse resolution (Fig. 1.3c). A relationship between MODIS Aerosol Optical Thickness (AOT) and ground-based hourly fine particulate ($PM_{2.5}$) has been shown (Hutchison, 2003; Wang & Christopher, 2003). The Measurement of Pollution in The Troposphere (MOPITT) instrument aboard the NASA Earth-Observing System (EOS) Terra satellite is a thermal and near infrared (IR) gas correlation radiometer, designed specifically to measure CO profiles and total column CH_4 (Figs. 1.3d and 1.4). The CO pollutant can also be used as a tracer for other pollutants, such as ozone at or near ground level (Edwards et al., 2003).

1.5. Environmental impacts

VFS can have impacts on the air, water, and soil. The long-term effects of vegetation fire emissions on atmospheric composition and global processes have been presented and discussed (Houghton et al., 1992). Short-term effects of forest fires include elevated trace gases, aerosol, and CO_2 levels, nitrogen deposition, acid precipitation, and local climatic changes (Bazzaz, 1990; Fan et al., 1990; Vitousek et al., 1997). Environmental impacts of VFS include the increase of the ground-level ozone, due to photochemical reactions of VFS components in the

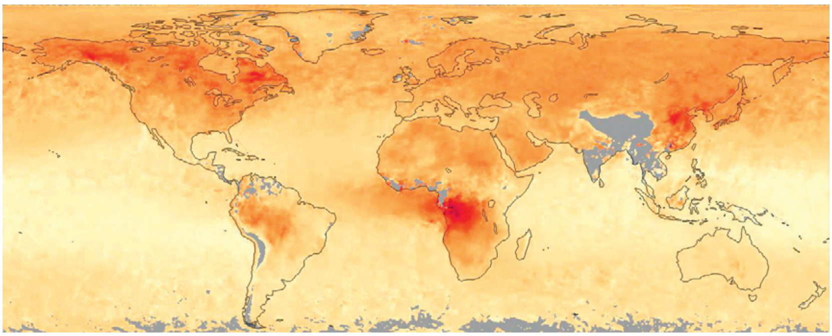


Figure 1.4. Global carbon monoxide (CO) concentrations in the Northern Hemispheric summer of 2004 depicted by the MOPITT sensor. A record fire season in Alaska in 2004 spread smoke across the Northern Hemisphere and elevated CO levels across North America and Europe. Red indicates high concentrations, while yellow indicates low concentrations. The high levels over China are caused by industrial and urban pollution. The high CO concentrations in sub-Saharan Africa are generated by savanna fires. The Alaskan fires released approximately 30 Tg (teragrams: 1 Tg = 1 million metric tons) of CO (NASA Earth Observatory, 2006).

presence of NO_2, CO, and VOCs, the ground-level O_3 precursors (Hogue, 2005). It has been reported that the big wildfires in Alaska and the Canadian Yukon during the summer of 2004 generated huge plumes of CO and other pollutants and affected large areas of the Northern Hemisphere by increasing ground-level O_3 (Barry, 2005). Moreover, according to another study, there was evidence that Canadian forest fires in 1995 changed the photochemical properties of air masses over Tennessee on days during the fire period (USDA, 2002). During the 1997–1998 SE Asia fire–smoke episode, enhanced concentrations of CO_2, and CH_4 were observed throughout the troposphere from eastern Java to the South China Sea (Heil & Goldammer, 2001). Additionally, it has been reported that photosynthesis of three tree species was reduced by the smoke-haze of 1997 in Indonesia, due to elevated aerosol and atmospheric pollutant levels (Davies & Unam, 1999). VFS particles can pollute surface water directly, by deposition, or can become part of the soil. In this case and after a rainfall, suspended soil particles, as well as dissolved inorganic nutrients and other materials, can be transferred into adjacent streams and lakes, reducing water quality and disturbing aquatic ecosystems balance. In sandy soils, leaching may also move minerals through the soil layer into the ground water (USDA, 1989) (also see Section III of this volume).

Recent research reveals that, as a consequence of climate change, mercury deposits once protected in cold northern forests and wetlands will increasingly become exposed to burning. Mercury is released to the atmosphere with fire smoke. Turetsky et al. (2006) quantified organic soil mercury stocks and burned areas across western boreal Canada; it was assumed that, based on ongoing and projected increases in boreal wildfire activity due to climate change, atmospheric mercury emissions will increase and contribute to the anthropogenic alteration of the global mercury cycle and to the exacerbating mercury toxicities for northern food chains.

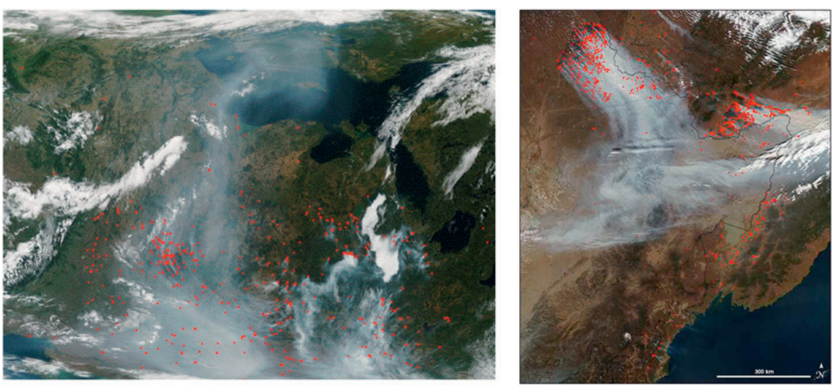
1.6. Peatland fires

The recurring regional VFS pollution in Southeast Asia, a phenomenon largely resulting from application of fire in land-use change and extended wildfires, has been observed since the 1980s. Despite the 2001 Association of Southeast Asian Nations (ASEAN) Agreement on Transboundary Haze Pollution that aimed at reducing regional smoke-haze caused by VFS, the inappropriate and illegal use of fire land vegetation conversion, especially on drained peatlands, is still practiced (Goldammer, 2006b). Recent public interest on emissions from peatland conversion fires is based on the controversial debate about the increasing conversion of peatlands to establish oil palm plantations as a source of "bioenergy".

While much public attention has been given to regional VFS pollution in Southeast Asia, there is limited scientific and public coverage on the transboundary transport and impacts of peat fire smoke on human health and security in the Northern Hemisphere.

The fact of the matter is that fires burning in drained or desiccated peatlands are an important source of extended fire smoke pollution in formerly cultivated and currently abandoned regions of northern Eurasia. In the western Russian Federation, peatlands have been drained and used for agricultural purposes since the early 19th century. The fen peatlands were used as agricultural fields but are out of use now. According to the Wetlands International Russia Program, peatland fires are a common phenomenon in the Russian Federation (Minaeva, 2002) and may contribute to about 10% of the total area burned (Shvidenko & Nilsson, 2000). In most cases, the fires are started outside the peatlands, caused by forest visitors, hunters, tourists, or by agricultural burning and burning activities along roads. In Fig. 1.5a, a satellite image of the western Russian Federation with heat signatures of peat and forest fires in 2002 is presented.

In September 2002, the VFS from peat and forest fires in the Moscow region reduced the visibility to less than 100 m in Moscow, where the concentration of CO exceeded the permissible values by more than three



(a) (b)

Figure 1.5. (a) Satellite scene of the western Russian Federation on September 4, 2002. The heat signatures of the peat and forest fires are given in red. The smoke plumes (light blue haze) stretch from the Western Russian Federation to Belarus, Poland, and the Baltic Sea. (b) Smoke transport from fires (marked in red) in northern China (top left) and the southeast of the Russian Federation (right) on October 15, 2004. (*Source*: True color image by Moderate-Resolution Imaging Spectroradiometer (MODIS), resolution 2 km.)

times (European Water Management News, 2002). The smoke pollution did not only cause a dramatic reduction of visibility but also had detrimental impacts on the health of the population and resulted in an increase of hospital admissions (also see Chubarova et al., this volume). In spring 2006, smoke from peat and forest fires in the western Russian Federation was noted in the United Kingdom. In summer 2006, VFS from fires burning in the Russian Federation persisted over Finland for weeks (GFMC, 2006). In Fig. 1.5b, transboundary transport of smoke due to fires in the northern China and the southeast of the Russian Federation during October 2004 is shown.

Short- to long-distance transport of smoke has also been noted within central and east Asia during the last 10 years. The fire episodes of 1998 (Far East), 2003 (Transbaikal region), and 2004 (Northeast China, Jewish Autonomous Region) caused severe smoke pollution in the Far East of the Russian Federation. The consequences of regional smoke pollution in 2004 were recorded in Khabarovsk and revealed that both aerosol and carbon monoxide concentrations exceeded the maximum permissible concentrations (Goldammer et al., 2004).

1.7. Impacts of VFS on visibility

Reduced visibility is the main impact of VFS on critical infrastructures. For instance, in 1994, VFS from fires in Sumatra (Indonesia) initially reduced the average daily minimum horizontal visibility over Singapore to less than 2 km. Later, the visibility in Singapore dropped to 500 m. At the same period, the visibility in Malaysia dropped to 1 km in some parts of the country (WHO/UNEP/WMO, 1999). Other impacts on infrastructures included the irregularities in operation of airports (reduced or cancelled flights), highways and hospitals, and even army camps. For example the regional airports in Indonesia were closed during the haze period of 1997. In 1982–1983, 1991, 1994, and 1997–1998, the smog episodes in Southeast Asia resulted in closing of airports and marine traffic. In addition, accidents in the highways or possible airplane crash and human losses can be the result of reduced visibility. Several smoke-related marine and aircraft accidents occurred during late 1997 (WHO/UNEP/WMO, 1999). From 1979 to 1988, 28 fatalities and more than 60 serious injuries were attributed to smoke that drifted across roadways in the southern United States (Mobley, 1990). According to a study concerning the 1998 smoke episode in Brunei Darussalam, it was found that the haze impact on areas where a school and a hospital were situated was significant (Muraleedharan et al., 2000). In Fig. 1.6, people

Figure 1.6. People exposed to VFS in East Kalimantan, Indonesia, during the 1997–1998 fire–smoke episode. (*Source*: A. Hoffmann, GFMC.)

exposed to VFS in East Kalimantan, Indonesia, during the 1997–1998 fire-smoke episode are presented.

Generally, limited data and case studies exist regarding VFS impacts on critical infrastructures for risk management (Dokas et al., 2007). In Fig. 1.7, reduced visibility in an urban area of Russian Federation due to transboundary smoke-haze transfer is shown.

1.8. Human health impacts of Vegetation Fire Smoke

1.8.1. Toxicity of VFS

Generally, toxicity is defined as the deleterious or adverse biological effects caused by a chemical, physical, or biological agent. Toxicity can be acute, defined as any poisonous effect produced within a short period of time, or chronic, defined as the capacity of a substance to cause adverse human health effects as a result of chronic exposure. To assess the risks

Figure 1.7. VFS pollution in Khabarovsk in the Far East of the Russian Federation caused by forest and peat fires in northeast China/Far East of the Russian Federation (March 11, 2008). (*Source*: L. Kondrashov, Pacific Forest Forum.)

from toxic substances, toxicity indicators can be used, such as the LC_{50} (concentration of a substance in the air at which 50% of the tested population is killed) or the EC_{50} (concentration of a substance in the air at which 50% of the tested population are affected (ContamSites, 2007). For evaluating chronic toxicity, the lowest observable effect concentration (LOEC) can be used. Although by themselves LC_{50} values are of limited significance, acute lethality studies are essential for characterizing the toxic effects of chemicals and their hazard to humans. The most meaningful scientific information derived from acute lethality tests comes from clinical observations and postmortem examination of animals rather than from the specific LD_{50} value (Eaton & Klaassen, 2001).

The toxic effects due to chemicals are also related to the duration of the exposure. Generally, exposure is defined as the contact made between a chemical, physical, or biological agent and an organism. Acute exposure is defined as exposure to the oral, dermal, or inhalation route for 24 h or less. Chronic exposure is the repeated exposure to the oral, dermal, or inhalation route for more than approximately 10% of the human life span. Risk assessment under specific exposure conditions is defined as the identification and evaluation of the human population exposed to a toxic agent, describing its composition and size, as well as the type, magnitude, frequency, route, and duration of exposure (EPA IRIS, 2007).

Toxicity of the VFS mixture can be the additive or the synergistic result of all the possible hazardous smoke components, depending on the fuel types burned and the possible materials contained in the VFS. Additive toxicity is defined as the toxicity of a mixture of contaminants that is equal to the summation of the toxicities of the individual components. Synergistic toxicity is defined as the toxicity of a mixture of contaminants that may result in a total toxicity greater than the summation of the toxicities of the individual components (ContamSites, 2007).

VFS may contain toxic compounds such as:

- *Respiratory irritants:* Irritants can cause inflammation of mucous membranes. Ammonia (NH_3) and nitrogen dioxide (NO_2) are indicative examples. Irritants can also cause changes in respiration and lung function, such as sulfur dioxide, formaldehyde, and acrolein (MSU, 2005). According to specific studies, formaldehyde and acroleine were suspected of causing respiratory problems to the exposed firefighters (Reinhardt & Ottmar, 2004; Reinhardt et al., 2000).
- *Asphyxiants:* Asphyxiants prevent or interfere with the uptake and transport of oxygen. An example is carbon monoxide, which in high concentrations can result in immediate collapse and death (MSU, 2005). Methane and carbon dioxide are also considered asphyxiants. Even beneficial gases can be asphyxiants: a 17% inhaled oxygen content is the safe limit for prolonged exposure. A 5% oxygen content is the minimum compatible with life. Concentrations of 1% produce stupor and memory loss (Stefanidou-Loutsidou, 2005).
- *Carcinogens:* A carcinogen is a chemical, known or believed to cause cancer in humans. The number of proven carcinogens is comparatively small, but many more chemicals are suspected to be carcinogenic (PTCL, 2007). Weight-of-evidence (WOE) for carcinogenicity is a system (U.S. EPA) for characterizing the extent to which the available data (human or animal data) support the hypothesis that an agent can cause cancer to humans. WOE descriptors are classified from A to E: group A are known human carcinogens, whereas group B are probable human carcinogens, group C possible human carcinogens, group D are not classifiable as human carcinogens, and E are compounds with evidence of non-carcinogenicity (EPA IRIS, 2007). Carcinogens can be of three categories: Category 1 are substances known to be carcinogenic to humans, for which there is sufficient evidence to cause

cancer development; Category 2 are substances for which there is sufficient evidence of causing cancer to humans, based on long-term animal studies and other relevant information; Category 3 are substances that can possibly have carcinogenic effects but for which available information is not adequate to make satisfactory assessments (UB, 2007). According to the above, benzene is considered as A, formaldehyde as B1, acetaldehyde as B2, crotonaldehyde as C, toluene and phenol as D (EPA IRIS, 2007).

- *Mutagens:* A mutagen is an agent that changes the hereditary genetic material. Such a mutation is probably an early step to the development of cancer, for example, formaldehyde, acroleine (PTCL, 2007). Teratogens may cause non-heritable genetic mutations or malformations in the developing fetus, for example, toluene (PTCL, 2007).
- *Systemic Toxins:* These are chemicals, which can cause toxic effects, as a result of their absorption and distribution to a site distant from their entry point (EPA IRIS, 2007). Examples are heavy metals, such as lead, mercury, and cadmium (Stefanidou-Loutsidou, 2005), which may be contained in the VFS particles, especially when the flame-front expands to waste disposals (landfills) (Statheropoulos & Karma, 2007).

1.8.2. Exposure

Exposure to VFS can be quantified as the concentration of the smoke components in the subject in contact integrated over the time duration of that contact. In order to have a more representative assessment of VFS health impacts, it should be considered that exposure to VFS is simultaneous exposure to multiple substances, such as gases, liquids, solids (mixed exposure). A potential synergism may exist among various VFS components.

Exposure can be characterized as point, area/surface or network; such exposure characteristics should be taken into account for addressing exposure limits. Temporal/averaged, discrete/sporadic or continuous/cumulative exposures have to be taken into account in order to calculate an averaged, sporadic, or cumulative exposure, respectively (Seyenaeve, 2006).

Firefighters' exposure to VFS is characterized mostly by a standard periodicity (every summer) and high frequency (e.g., long-lasting fires). Hence, the ability to measure online their exposure is considered critical. Exposure of the firefighters to CO and formaldehyde can exceed legal and short-term exposure limits, occasionally, in smoky conditions; CO level has been noted as exceeding the 200 ppm ceiling set by the NIOSH (Reinhardt et al., 2000).

Exposure of general populations to VFS is not a continuous situation. However, susceptibility of the receptors should also be taken into consideration during exposure assessment, as sensitive groups, such as children, pregnant women, people with respiratory problems, and the elderly are considered more vulnerable (USEPA, 2001).

Different organizations have evaluated compounds that are considered hazardous for the exposed populations. The WHO, European Union (EU), United Nations Economic Commission for Europe (UNECE), and United States Environmental Protection Agency (USEPA) are some of those organizations. In that scope, terms such as standards, guidelines, and limit values are used. EU limit values are mandatory, while guide values give only guidance. Standards (or EU Directives) can contain both limit and guide values (Colls, 2002). Additionally, the ACGIH has established Threshold Limit Values (TLVs), the Occupational Safety and Health Administration has addressed Permissible Exposure Limits (PELs), and the NIOSH has addressed Recommended Exposure Limits (RELs). These limits are referred to as the occupational exposure of 8 h or 24 h, and for some compounds the Short-Term Exposure Limits (STELs) of 15 min exposure are also given.

However, these Occupational Exposure Limits (OELs) need further investigation. For example, TLVs are based on a young and healthy worker, which might not be representative for the entire exposed population. Moreover, inhalation is considered the main route of exposure and the exposure pattern is 8 h/day/5 days/week (Seyenaeve, 2006). In emergency situations work-shifts of the firefighters are often extended.

For unusual schedules, adjustments of these limits to the extended work-shifts need to take place (Kelly, 1992; Reh & Deitchman, 1992). Threshold limits for the firefighters' exposure to VFS is an issue that needs further study. The time duration of the shifts varies, depending on the extension of the fire. In addition, the distance of the shift camping from the fire-front is usually not far enough for the firefighter to recover from smoke inhalation. Camping some distance from the fire and smoke front is a problem, especially in the case of forest fires in small islands, where dispatching means and personnel is difficult (Statheropoulos, 2005).

Especially for the exposure to particles, during a vegetation fire very high concentrations of particles at short-time duration may be observed; these short-term peaks may cause some of the most significant health implications. Fine particles, known as respirable, are not stopped by the cells of the respiratory tracts and can penetrate the lungs more easily than coarse particles. In this way, hazardous compounds absorbed by the fine particles can reach the air cells (Cesti, 2006; Dawud, 1999; Fowler, 2003; Malilay, 1998). Toxic effect of particles is related to the quantity of toxic substances that may be absorbed and the affinity for site of action (enzyme, membrane). In general, biological absorption of particles by the human body can take place by filtration through pores of membranes, simple diffusion, facilitated diffusion, active transport (against concentration gradient), or endocytose (pinocytose-phagocytose). Biological absorption can be oral, pulmonary, cutaneous, ocular, etc. Some of the health effects due to particles can be acute toxicity, skin corrosion/irritation, serious eye damage/eye irritation, sensitization (allergy), carcinogenicity, specific target organ systemic toxicity (TOST), respiratory irritation, and so forth (Seyenaeve, 2006). Hence, the 24 h assumption of particles for OELs might not be efficient for short-term risk assessment in a vegetation fire. It should be emphasized that official exposure limits for particles near the flame-front do not exist. However, there was an effort to provide some criteria, in order to assess the severity of the situation in a forest fire (USEPA, 2001). Adjustment of the existing exposure limits to the hostile conditions of vegetation fires has to be taken into consideration not only for the exposed population and its sensitive groups, but also for the firefighters of the front-line. In addition, exposure limits to VFS components should be addressed in the framework of field exposure, compared to occupational indoor exposure.

1.9. Conclusions and recommendations

VFS has serious impacts on the environment and human health, as well as the national economy (Rittmaster et al., 2006). Strategies and tactics exist to cope with its impacts. However, a number of issues are still open for further elaboration and decision making. Therefore, the Health Guidelines for Vegetation Fire Events (WHO/UNEP/WMO, 2000), dealing with potential risks to public health of emissions from vegetation fires, recommend that additional research be conducted to address:

- Quantification of resulting concentrations of ambient air pollutants in populated areas.
- Evaluation of likely exposure scenarios for affected populations (both indoors and outdoors).
- Assessment of consequent health risks posed by such human exposures.
- Special attention to fire-generated radioactive emissions.
- Physical/chemical factors contributing to the changes that occur over time and space during VFS transport.

- Compilation of information pertaining to levels of exposure and fire activity, in conjunction with past fire and smoke episodes.
- Mitigation approaches.
- Health impacts ofVFS.

In addition, a "catalogue of ideas" was prepared in the framework of a teleconference entitled "Short- and long-term health impacts of forest fire smoke on the firefighters and the exposed population" (FFNet, 2005), which was organized in 2005 by the European Center for Forest Fires (ECFF), a center that operates in the framework of the European Open Partial Agreement (EUROPA) on the prevention, protection against, and organization of relief in major natural and technological disasters. Some of these ideas are:

- Forest fire smoke is a complex mixture of chemical compounds produced from combustion of forest fuel. However, as fire expands, it may burn constructions, landfills, or crops. Asbestos, glass cement, and combustion products of plastics, pesticides, insecticides can potentially be found in forest fire smoke. Data need to be collected regarding this concept.
- Exposure limits for the firefighters need to be established, taking into consideration the complexity of smoke, the dynamic phenomena which occur during a forest fire, the nature of firemen's work, the duration of work-shifts, and the site of the shift camping. Research and studies, with strong operational components, might be the way for providing solutions.
- Exposure limits for the population and especially for the sensitive groups, such as infants, elderly people, pregnant women, and people with pre-existing cardiovascular and respiratory diseases have to be set and criteria of evacuation need to be considered. Evaluation of existing or similar studies needs to be carried out.
- Existing Personal Protective Equipment (PPE) needs to be benchmarked with careful experimentation.

1.10. Challenges ahead: Public policies addressing wildland fire smoke

The primary aim of this chapter was to provide a state-of-the-art report on the nature of VFS emissions. Exposure and vulnerability of humans to fire emissions, however, is a subject that needs more information on options for limiting smoke impacts on human health and security. A number of recent VFS pollution episodes have caused public concerns and alerted policy makers. Some responses, such as calls or laws for eliminating the use of fire in land management, have resulted in conflicts, contradicting effects, or are difficult — if not impossible — to enforce. Examples include the fire-use ban in Indonesia, which has been in force since the mid-1990s and has been proven to be ineffective. As discussed above, the ASEAN Agreement on Transboundary Haze Pollution, signed by the ASEAN member states in 2001 and aimed at reducing regional smoke-haze caused by VFS, has proven to be inefficient—largely because Indonesia was not willing and able to reduce inappropriate and illegal use of fire in land-use change, especially on drained peatlands (Goldammer, 2006b).

An example of contradicting effects is the reduction of prescribed burning in the U.S. due to limitations imposed by the U.S. Environmental Protection Agency standards. These limitations have resulted in a reduction of application of prescribed fire for various land management objectives in the 1980s and 1990s. Clearly, smoke products from prescribed fire are basically identical with those emitted from uncontrolled wildfires, even if differences have been revealed, such as ratios of oxidized/reduced compounds, for example, NO_x/NH_3 (Ward et al., 1993). The application of prescribed fire includes smoke management options, which will reduce smoke impacts on humans. The reduction of prescribed burning, however, results in the build-up of fuels, which in turn contributes to the risk of large, high-intensity and high-severity fires that are difficult to control, including uncontrollable and comparatively more severe impacts of smoke.

Besides the implications of fire bans on potentially uncontrolled fires and smoke production, it must be reminded that fire exclusion from fire-adapted or fire-dependent ecosystems, which require a regular influence of fire, can also result in dramatic changes of structure, biodiversity, stability, and productivity of such ecosystems. Therefore, a complete exclusion of fire from land-use systems would affect livelihoods of hundreds of millions of people worldwide.

However, the transboundary transport of VFS from one country to another country is increasingly the subject of public and political debates. Three recent cases may highlight this issue. In May 2006 western Europe including the United Kingdom was affected by fire smoke pollution generated and transported from vegetation burning in the western Russian Federation. As a consequence of the high concentration of PM_{10} monitored in the United Kingdom, the UK Department for Environment, Food and Rural Affairs (DEFRA) announced that the UK government was going to submit revisions to the United Nations Convention on long-range transboundary air pollution to prevent similar occurrences in the future (GFMC, 2006).

In August 2006, the VFS emissions from the western Russian Federation, Ukraine, and Belarus were transported to the Nordic countries. Smoke exposure was particularly severe in Finland where the air pollution exceeded the limits of the maximum permissible amount of airborne dust in city air of 50 micrograms per cubic meter of air for almost 2 weeks. In order to deal with this transboundary process, a joint Russian-Finnish wildland fire exercise was held in Karelia (Finland) soon after these events (GFMC, 2006).

In March–April 2007 the fire smoke generated by numerous land-use fires in northern Thailand, Myanmar, Laos, China, and Cambodia caused extremely severe regional smoke pollution. The situation was aggravated by a very strong inversion event, which trapped the smoke close to the ground. This resulted in a situation similar to the close-to-ground pollution in southern Malaysia and Singapore as a consequence of Indonesia's land-use fires. Tensions and international discussions on defining common solutions were reported from the region (GFMC, 2007a).

The consequences of fire burning on radioactively contaminated lands and its consequences on redistribution of radioactive particles lifted by fire smoke is another serious issue that needs to be addressed. In the case of the Chernobyl nuclear accident of 1986 and its implications on the redistribution of radioactivity by wildfires, a new initiative has been launched in 2007 by the Agricultural University of Kiev, Ukraine, to address the problem to reduce the contamination locally, nationally, and transnationally (GFMC, 2007b).

These examples reveal the transboundary and international nature of VFS emissions that can cause many problems, in an increasingly vulnerable global society. These problems have to be addressed cooperatively and collectively. Consequently, bilateral and multilateral agreements are necessary to address these issues. An international agreement—legally binding or voluntary—could be helpful to set standards for prevention and response to VFS pollution. The use of the WHO/UNEP/WMO Health Guidelines for Vegetation Fire Events (WHO/UNEP/WMO, 1999), the Voluntary Fire Management Guidelines (FAO, 2006), the Global Fire Monitoring Center (GFMC), and the mechanism of the UNISDR Global Wildland Fire Network (UNISDR, 2007) are available and could be applied to facilitate such an international approach.

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