18 Vegetation Fire Smoke Emissions and Human Health

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Abstract

Air pollution generated by vegetation fire smoke 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. Exposure and vulnerability of humans to fire emissions is a subject that needs more information on options for limiting smoke impacts on human health and security. A number of recent vegetation fire smoke 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. 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.

Keywords: Vegetation fire smoke, fire smoke compounds, fire smoke toxicity, radioactivity, smoke impacts on human mortality

Introduction

Air pollution generated by vegetation fire smoke (VFS) is a phenomenon that in many cases it has influenced the global environment. 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

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Table 18.1. Chemical composition of smoke of vegetation fires burning in the interface of rural, urban, or industrial areas, based on the flame-front and smoke dispersion pathway.

	Vegetation fire flame-front pathway	**Rural fields**	**Rural or urban constructions**
Physical/ Chemical processes:	Pyrolysis and combustion of forest fuel	Pyrolysis and combustion of agricultural fields, fungicides, fertilizers, pesticides e.g. 4-chloro-2-methyl phenoxy acetic acid (MCPA)	Pyrolysis and combustion of paint, glue, wood, plastics) Glass, cement, plaster, asbestos can be contained in the smoke produced
Chemical components:			
a) Organic	a) VOCs (Hydrocarbons, Aldehydes, furans, carboxylic acids, BTEX), SVOCs (PAHs)	a) VOCs, SVOCs (PAHs), PCDDs, PCDFs	a) Non polar VOCs (e.g BTEX, styrene), SVOCs (PAHs), PCDDs, PCDFs, PCBs
b) Inorganic	b) CO, CO_2, NO_X, SO_x, trace elements (e.g. S, Cl, K, Na, Mg, Cu, Ni, Cu, Zn)	b) CO, CO_2, CH_4, HCl, SO_2, NO_X, PO_x, NH_3, CS_2, H_2S, HCN	b) CO, CO_2, metals (e.g. Ca, Mg, Ti, Al)
Physical properties:			
a) particle size	a) Coarse (PM_{10}) & fine ($PM_{2.5}$)	a) Coarse (PM_{10}) & fine ($PM_{2.5}$)	a) Coarse (PM_{10}) & fine ($PM_{2.5}$)
b) particle shape	b) Spherical, fibrus		
Chemical properties:			
a)Alcalinity / acidity			a) Alkaline pH
b)Photo-chemical reactions			

Landfills	Illegal waste disposal	Forest fire retardants	Smoke pathway	Urban or Industrial areas
Pyrolysis and combustion of household waste, plastic, rubber, paper, Glass and metals can be contained in the smoke produced	Pyrolysis and combustion of organic residues, lead-acid vehicle batteries, electric appliances, radioactive materials	Pyrolysis and combustion of diammonium phosphate (DAP), ammonium sulfate & other commercial retardants	Mixture of gases, liquids & solids	Mixing of forest fire smoke with urban and industrial pollutants, possible photochemical reactions
a) VOCs, chloro-benzenes, chloro-phenols, SVOCs (PAHs), Carbonyls, PCDDs, PCDFs, PCBs	a) PCDDs, PCDFs, Co-PCBs			a) Aliphatic H/C, VOCs, BTEX, Styrene, PAHs, Saturated hydrocarbons (PAR), mercaptans
b) CO, CO_2, heavy metals (e.g. Pb, Cd, Cr, Cu, Zn)	b) CO, CO_2, radionuclides (I-29, Cs-137, Cl-36)	b) NH_3, SO_2		b) CO, CO_2, NO_X, SO_2, H_2S, O_3
a) Mainly fine particles ($PM_{2.5}<$)		a) Mainly fine particles ($PM_{2.5}<$)		a) Coarse (PM_{10}) & fine ($PM_{2.5}$)
				b) Irregular
				b) PAH photo-degradation, photo-chemical O_3

droughts that are attributed to inter-annual climate variability, or are possible consequences of regional climate change. In metropolitan or industrial areas, the impacts of VFS may be coupled with the emissions burden from fossil fuel burning and other technogenic sources, resulting in increasing adverse affects on the human population. Possible chemical synthesis of the smoke produced in different scenarios of a forest fire, burning near rural, urban or industrial areas is given in a format of a road-map for air-quality assessment (Tab. 18.1) (Statheropoulos and Karma, 2007). Special emphasis should be given on radioactive emissions generated by fires burning in peatlands and on terrain contaminated by radionuclides.

A global perspective regarding the impacts of vegetation fire emissions on the environment, human health and security has been presented recently (Goldammer et al., 2009). Generally, during vegetation fires, high peak concentrations of VFS components can be observed, especially near the flame-front. Table 18.2 presents mean concentrations of VFS components measured under "smoky" conditions in the field (sampling duration 20-30 min) that have been reported in the literature (Miranda et al., 2005; Pinto and Grant, 1999; Reinhardt et al., 2000; Statheropoulos and Karma, 2007).The respective quideline values. for outdoor environment, as published by the Word Health Organization (WHO Guidelines for Air Quality, 2000 and WHO Air Quality Guidelines Global Update, 2006) are also given. However, these values could be more appropriate in order to evaluate exposure of the general population. Only the BaP recommended exposure limit provided by the U.S. National Institute for Occupational Safety and Health (NIOSH) refers to occupational health.

Table 18.2. Mean concentrations measured in smoky conditions in the field and respective guideline values given by WHO (2000)

Compound	Concentration	Guideline value (ppm)	Averaging time
[1]CO	54 ppm	50	30 min
[2]Benzene	0.22 ppm	[a]0.0016	1 year
[2]Toluene	0.12 ppm	0.27	30 min
[2]Xylene	0.08 ppm	1.1	24-h
[1]Acroleine	0.071ppm	0.02	30 min
[1]Formaldehyde	0.468 ppm	0.08	30 min
[3]BenzoPyrene (BaP)	7.1 ngm^{-3}	[b]100 μg m^{-3}	8-h
[1,4]$PM_{2.5}$	[1,2]7,000 μg m^{-3}, [4]2,300 μg m^{-3}	[c]25 μg m^{-3}	24-h

[1]Reinhardt et al. (2000); [2]Statheropoulos and Karma (2007); [3]Pinto and Grant (1999), [4]Miranda et al. (2005)

[a]Directive 2008/50/EC, [b]NIOSHREL (2012), [c]WHO (2006)

VFS produced by large vegetation fires is usually transported many kilometres away from the source. Usually, fine particles can be transported to long distances (cross border transfer). During the El Niño episode in Southeast Asia in 1997-98, the smoke-haze layer covered an area up to 10×10^6 km^2 (Nakajima et al., 1999; Heil and Goldammer, 2001). 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 two weeks in the southeastern and eastern coastal United States during the summer of 1995 (Wotawa and Trainer, 2000).

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. VFS may contain toxic compounds such as (Statheropoulos and Goldammer, 2007):

- 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 sulphur dioxide, formaldehyde, and acroleine. According to specific studies, formaldehyde and acroleine were suspected of causing respiratory problems to the exposed firefighters
- 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. Methane and carbon dioxide are also considered asphyxiants. The Safety Booklet of Jefferson Lab, 2008 quotes the following table of health impacts of oxygen deficiency (Tab. 18.3)

Table 18.3 Oxygen deficiency and the relevant health effects

Percent Oxygen	Health Effects
17	Night vision reduced; Increased breathing volume Accelerated heartbeat
16	Dizziness; Reaction time for new tasks is doubled
15	Poor judgment; Poor coordination; Abnormal fatigue upon exertion; Loss of muscle control
10-12	Very faulty judgment; Very poor muscular coordination; Loss of consciousness
8-10	Nausea; Vomiting; Coma
< 8	Permanent brain damage
< 6	Spasmodic breathing; Convulsive movements; Death in 5-8 minutes

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. International Agency on Research on Cancer (IARC) have classified the chemical agents into different groups depending on their impact on humans. Group 1 includes agents carcinogenic to humans, Group 2A are probably carcinogenic to humans, Group 2B are possibly carcinogenic to humans, Group 3 are not classifiable as to its carcinogenicity to humans and Group 4 are probably not carcinogenic to humans. According to IARC, benzene, benzo[a]pyrene and formaldehyde are Group 1 carcinogens ('Sufficient evidence in humans or sufficient evidence in animals and strong mechanistic data in humans'). Usually guideline values are given by WHO in terms of unit risks which refer to lifetime exposure.

- 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.
- Teratogens may cause non-heritable genetic mutations or malformations in the developing fetus, for example, toluene
- 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. Examples are heavy metals, such as lead, mercury, and cadmium, which may be contained in the VFS particles, especially when the flame-front expands to waste disposals (landfills).

In order to achieve a more representative assessment of VFS health impacts, VFS exposure should be considered as combined exposure to multiple chemicals. Combined exposure to multiple chemicals is defined in the context of whether or not the components act by similar or different modes of action in induction of critical effect (WHO/IPCS, 2011).

The exposure of firefighters to VFS is characterized mostly by a standard periodicity (every summer) and duration (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).

Emissions from Fires Burning on Contaminated Terrain

In some countries forests and other lands are contaminated by various types of hazardous chemical and radioactive pollution. Wildfires occurring in such contaminated terrain may result in secondary air pollution. The territories most affected by radioactive pollution have been contaminated by the release of radionuclides during the failure of the Reactor Number Four of the Chernobyl Nuclear Power Plant in 1986. Among the total 6×10^6 ha of

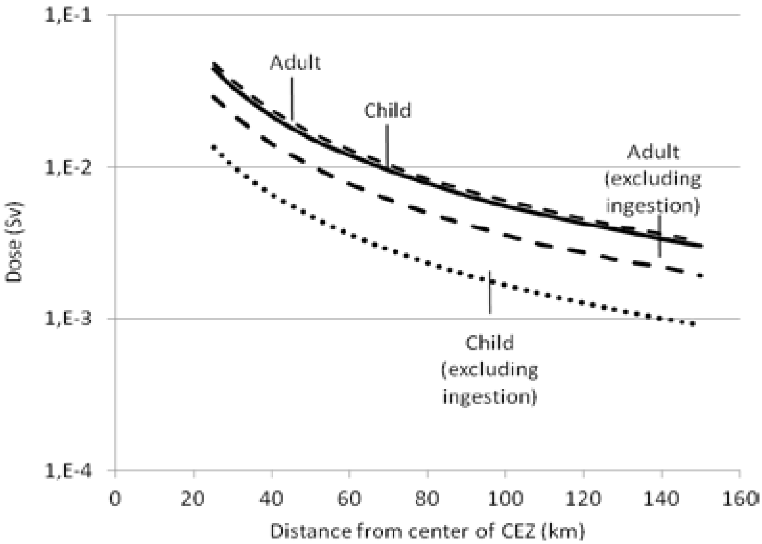

Figure 18.1. Estimated total dose (Sv) (with and without ingestion), as a function of distance from the center of the CEZ, that could be received by children (1 year old) and adults during the year following a catastrophic wildfire (Hohl et al., 2012).

radioactively contaminated terrain in Ukraine, Belarus and Russia the most polluted forest area covers over 2×10^6 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 was found to be caesium-137 (^{137}Cs); in the core zones of contamination, strontium-90 (^{90}Sr) and plutonium-239 (^{239}Pu) were found in high concentrations. Generally, below 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 (see reviews by Goldammer et al. [2009] and Hao et al. [2009]).

The Chernobyl Wildfire Project, consisting of scientists from the Ukraine, U.S.A., and Germany, developed a model to assess the potential implications of a catastrophic wildfire the Ukrainian portion of the Chernobyl Exclusion Zone (CEZ) on populations living and working near the CEZ. The complete model consists of a source model, a transport model, and an exposure model. As a worst case scenario, it is assumed that a fire would consume the biomass of pine forests and former agricultural lands and release any associated radionuclides into the atmosphere. The transport model assumes that the wind would blow primarily towards Kiev throughout the fire event.

The exposure model estimates adult and child (1 year old) external exposures and doses via five exposure pathways. Excluding the food ingestion pathways, calculated doses to populations at distances 30 km or greater from the release point are less than the critical thresholds that would require evacuations. However, Ukrainian law would require limiting consumption of certain foodstuffs to avoid exposure through ingestion.

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 of food chains in the northern hemisphere.

Other contaminated terrains are former gold mining areas, e.g. calcine sand deposits in Victoria (Australia), which are a by-product of past gold mining methods and contain small amounts of arsenic and mercury. They became airborne after vegetation cover was burnt by a wildfire in February 2009 ("Black Saturday Fire"). The threat of uncontrolled airborne distribution of arsenic and mercury was controlled by site rehabilitation a year later (Anonymous, 2010).

Evidence of Smoke Impacts on Human Mortality

Although the land-use fire and smoke pollution episode in South East Asia in 1997-98 created an interest of the scientific community to assess the impacts of vegetation fire smoke pollution on human health and mortality and prompted the United Nations to evaluate the state-of-the-art knowledge on the scientific base of VFS and measures of health protection (Schwela et al., 1999 a, b, c; Heil and Goldammer, 2001), only occasional narratives and evidence are available. While general narratives described extended smoke pollution episodes in all continents during recent years, these episodes have not been utilized sufficiently for in-depth research, clinical studies and collection of statistical information on hospital admissions, immediate consequences on public health or premature deaths.

Recently reported numbers of populations affected by smoke pollution include government reports published in the media, e.g. those reported after the fire and smoke episode in Western Russia in 2010 or in Thailand in 2012. According to official statistics of the Economic Development Ministry of the Russian Federation the number of deaths during the months July and August 2010 in Russia exceeded the number of deaths in the same period of 2009 by 55,800.[3] While an increase of premature deaths could be attributed to both of combined impacts of the extreme heat wave and the long-lasting VFS pollution, a study of daily fine particulate matter ($PM_{2.5}$) concentrations using MODIS satellite observations of aerosol optical depth (AOD) led to the conclusion that that exposure to air pollution from the 2010 wildfires "*may have caused hundreds of excess deaths*" in Moscow Region (van Donkelaar et al., 2011). An evaluation of the daily number of deaths by age group (all ages, <75 and ≥75 years) provided by the Hellenic Statistical Authority for all natural, cardiovas-

3 Report of the Economic Development Ministry of Russia, published in The Moscow Times, 27 October 2010, on file at the GFMC repository: http://www.fire.uni-freiburg.de/media/2010/10/news_20101027_ru.htm

cular and respiratory causes during a large fire episode in Greece in 1998 by Analitis et al. (2011) showed that the fires were associated with a significant increase in the daily number of deaths: 50% increase in the total daily number of deaths, 61% increase in the number of cardiovascular deaths (78% for those <75 years old and 55% for those ^{3}75 years old) and 92% increase in the daily number of respiratory deaths (72% for those <75 years old and 101% for those $75 years old). The effects on total and cardiovascular mortality were higher during the days of the fires, while the lagged effects are larger for respiratory mortality (Analitis et al., 2011).

The annually recurring episode of agricultural burning in mainland Southeast Asia during the dry season (between January and April) is regularly resulting in extended near-ground VFS pollution. In early 2012 extended smoke pollution affected the North of Thailand. The Provincial Disease Control Office in Chiang Mai reported that in February-March 2012 more than 240,000 people sought medical treatment for haze-related illnesses at 87 hospitals in the eight northern provinces of Thailand. The official tally recorded over 100,000 patients with coronary heart disease, another 100,000 patients with respiratory diseases and about 20,000 persons suffering from eye inflammation and dermatitis.[4]

A first attempt to model global mortality attributable to VFS by Johnston et al. (2012) involved combining outputs from a chemical transport model with satellite-based observations of aerosol optical depth to estimate daily and annual exposure to $PM_{2.5}$ globally. In World Health Organization (WHO) subregions classified as sporadically impacted by VFS, the daily burden of mortality was estimated using previously published concentration-response coefficients for the association between short-term elevations in $PM_{2.5}$ from VFS and all-cause mortality. In subregions classified as chronically impacted, the annual burden of mortality was estimated using the American Cancer Society study coefficient for the association between long-term $PM_{2.5}$ exposure and all-cause mortality. Strong La Niña and El Niño years were compared to assess the influence of inter-annual climatic variability. The principal estimate for the average mortality attributable to VFS exposure was 339,000 deaths annually. In sensitivity analyses the interquartile range of all tested estimates was 260,000 to 600,000. The regions most affected were Sub-Saharan Africa (157,000) and Southeast Asia (110,000). Estimated annual mortality during La Niña was 262,000 compared with 532,000 during El Niño.

While the authors of the study are anticipating that subsequent estimates will be improved by better exposure assessment (particularly as empirical PM data become more globally available) and further epidemiologic studies on mortality and morbidity associated with landscape fire smoke (particularly in regions with high exposure), this assessment will require an in-depth review. Guidelines for reducing VFS impacts on human health, however, are available and will support decision making for policy and response (Schwela et al., 1999a; OEHHA and USEPA, 2008).

4 Report of the Economic Provincial Disease Control Office of Chiang Mai, published on 24 March 2012, on file at the GFMC repository: http://www.fire.uni-freiburg.de/media/2012/03/news_20120322_th.htm

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