A REVIEW OF FACTORS AFFECTING
THE HUMAN HEALTH IMPACTS OF AIR
POLLUTANTS FROM FOREST FIRES

Josephine Malilay

Division of Environmental Hazards and Health Effects
National Center for Environmental Health
Centers for Disease Control and Prevention
Atlanta, GA 30341-3724 USA

SUMMARY

Although total emissions and adverse health effects have been
documented in past studies, the overall toxicity of exposure to smoke or haze
from forest fires has yet to be fully evaluated. A review of the literature
identifies potential factors that influence forest fire emissions and allows for
extrapolation of possible health effects. Fire dynamics involves fire, fuel,
and climatological factors. The ecosystem’s chemical and physical features
combined with environmental parameters (humidity, temperature, and wind
speed) and the type of ignition, affect the combustion factor and efficiency
and, therefore, the amount of biomass consumed, the composition of smoke
emissions, and the rate of release of emissions. Characteristics of fuel (e.g.,
arrangement, size distribution, moisture, and chemical composition) affect
the phases of combustion, for which the quantities and rates of releases vary.
Exposure to combustion products can have potentially detrimental short and
long term effects on human health. These products, their known health
effects, and the factors influencing their effects are described for (1)
particulate matter; (2) polycyclic aromatic hydrocarbons; (3) carbon
monoxide; (4) aldehydes; (5) organic acids; (6) semivolatile and volatile
organic compounds; (7) free radicals; (8) ozone; (9) inorganic fraction of
particles; (10) trace gases and other releases; and (11) radionuclides. The
biological aspects of severe aerosol loading require further investigation.
INTRODUCTION

Given the objective of protecting public health, a complete understanding of the spectrum of health effects from biomass fires requires knowledge of the full range and potential of factors that might affect health outcomes and related impacts. Although total emissions and adverse health effects have been documented in public health and medical literature, the overall toxicity of exposure to smoke or haze has yet to be fully evaluated. A review of the current literature, primarily from atmospheric chemistry, identifies several factors that potentially influence the impact of air pollutants from forest fires on the susceptibility of individuals and vulnerable groups. Knowledge of adverse effects on public health from direct and indirect linkages is lacking, and efforts to elucidate the biological mechanisms by which exposures to biomass smoke affect human health have yet to be described. However, an extrapolation of potential factors on health effects can be attempted, taking into consideration biological plausibility, linkage between cause and effect, and coherence of past and current studies.

FIRE DYNAMICS AND THE COMBUSTION PROCESS

Fire dynamics is a complex process involving fire, fuel and climatological factors including altitude and meteorology. Under ideal conditions (i.e., complete combustion), the burning of organic material is an oxidation process that primarily produces water vapor and carbon dioxide (CO$_2$) (1). In natural and anthropogenic fires, combustion is incomplete due to an insufficient supply of oxygen (O$_2$). As a result, incompletely oxidized compounds (e.g., carbon monoxide) or reduced compounds (e.g., methane, nonmethane hydrocarbons, ammonia) are formed (1). These compounds are found in smoke, which often consists of irritant respirable particles and gases, and in some cases may be carcinogenic. Smoke itself is a complex mixture with components that depend on fuel type, moisture content, fuel additives such as pesticides sprayed on foliages or trees, and combustion temperature (2).

The combustion process involves two key parameters: the amount of biomass material burned and the proportion of a compound released during combustion, or emission factor, which is measured by grams (g) of pollutant
per kilogram (kg) of fuel consumed. Combustion efficiency, defined as the ratio of carbon released by the fire as CO$_2$, is a fundamental parameter that integrates many of the variables affecting biomass volatilization and oxidation (3). The ecosystem’s chemical and physical features combined with environmental parameters (humidity, temperature, wind speed) and the type of ignition, affect the combustion factor and combustion efficiency and, therefore, the amount of biomass consumed, the composition of smoke emissions, and the rate of release of emissions (4).

Combustion can consist of several phases relative to the time after ignition: (i) flaming phase, 0-20 minutes; (ii) initial smoldering phase, 20-80 minutes; and (iii) smouldering phase, 80-200 minutes. These processes are different phenomena involving different chemical reactions that result in diverse products (3). Characteristics of fuel (e.g., arrangement, size distribution, moisture, and chemical composition) affect the duration of each phase (3). The relative amount of biomass consumed through flaming and smoldering combustion can also vary due to these factors (4).

Exposure to combustion products can have potentially detrimental short and long term effects on human health. Although some of these products have been observed to occur in varying amounts after biomass fires (5, 6), little or no information exists about the intensity of human exposure and resulting health effects. The products, their known health effects, and the factors influencing their effects have been described for particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), aldehydes, organic acids, semivolatile and volatile organic compounds (VOCs), free radicals, ozone, inorganic fraction of particles, trace gases and other releases, and radionuclides.
COMBUSTION PRODUCTS OF BIOMASS FUELS

Particulate matter (PM)

**Health effects**

The solid component of smoke is PM, which at respirable size presents risks to human health. The PM mass is categorized into two modes: fine particle, with a mean-mass diameter of 0.3 micrometers (µm), and a coarse particle, with a mean-mass diameter greater than 10 µm. Even at low concentrations, fine particles have been observed to cause changes in lung function, leading to increases in respiratory and cardiovascular mortality and morbidity including asthma. Fine particles may reach the alveoli, and if not sufficiently cleared in the lungs and in great concentrations, may enter the bloodstream or remain in the lung, resulting in chronic lung disease such as emphysema. Airborne particulates may also contain toxic recondensed organic vapors, such as PAHs, which are indicated to be carcinogenic in animals (7).

**Factors affecting health effects**

The size of the fire event may influence resulting health effects. Particulate matter is produced abundantly, at least 0.6 tons per second after large fires, during forest fire combustion (8). 40 to 70 per cent of fine PM consists of organic carbon material, containing known carcinogens (9). 2-5 per cent is graphitic carbon; the remainder inorganic ash. Particulate matter may carry absorbed and condensed toxicants, and possibly, free radicals.

**Polycyclic aromatic hydrocarbons (PAHs)**

**Health effects**

PAHs comprise a group of organic compounds with two or more benzene rings, such as methyl anthracene, pyrene, chrysene, benzo(a)anthracene, fluoranthene, and methylchrysene. Benzo(a)pyrene is considered the most carcinogenic. Exposure to PAHs has been linked to lung cancer in railway workers exposed to diesel exhaust fumes and occupational lung cancer in coke oven and coal gas workers (7).

**Factors affecting health effects**
Factors related to combustion may affect the production and quantity of PAHs released into the atmosphere. Although little is known about which combustion conditions yield highest amounts of PAHs, some combustion conditions produce PAHs more abundantly than others. Low intensity backing fires (i.e., a line of fire moving into new fuel in an upwind direction) are found to produce larger amounts of benzo(a)pyrene than heading fires, which move into new fuel in the same direction as the wind movement (10). In one study, the amount of benzo(a)pyrene ranged from 98 µg/g to 274 µg/g of PM for low intensity backing fires and 2 µg/g to 3µg/g for heading fires (11).

Fuel characteristics also affect the production of PAHs during combustion. Emission of benzo(a)pyrene increased as the density of live vegetation covering the prescribed fire units thickened (5). Under natural conditions of a tropical medium such as savanna fires, PAHs were observed to be abundantly produced, mainly in gaseous form. The total flux of PAH emitted in tropical Africa during the biomass burning season is estimated to be 605±275 tons per year for gaseous PAHs and 17±8 tons per year for particulate PAHs. Although savanna fires occur during only a few months of the year, their contribution to the global burden of atmospheric PAH is significant compared to anthropogenic sources (12).

In wind tunnel simulations of open burning, emission factors for 19 PAHs were measured for agricultural and forest biomass fuels, including cereal grasses, agricultural tree prunings, and fir and pine wood. Yields of total PAH varied from 5 milligrams (mg)/kg to 685 mg/kg depending on burning conditions and fuel type; barley straw and wheat straw emitted PAHs including benzo(a)pyrene at much higher levels than other cereals and wood fuel types. Total PAH emission rates increased with increasing particulate matter emission rates and with declining combustion efficiency (13).

Studies from wood stoves indicate that higher burn rates lead to fewer total organic emissions but the proportion of PAHs increases (5). Emission rates for PAHs were observed to be highest for temperatures in the range 500-800°C (14), and were consistent with results from a study of PAHs released in low intensity backing fires (9,11). The emission and mutagenic activity of PAHs from small wood stoves were observed to be greatly influenced by the quality of wood, with high levels (10-30 mg PAH) detected per kilogram of virgin wood (15).
Carbon monoxide (CO)

Health effects

Carbon monoxide gas causes tissue hypoxia by preventing the blood from carrying sufficient oxygen (16). At low to moderate concentrations, health effects include impaired thinking and perception, headaches, slow reflexes, reduced manual dexterity, decreased exercise capacity, and drowsiness. At higher concentrations, death may result. Persons at higher risk include those with preexisting cardiovascular and respiratory disease, infants, the elderly, and pregnant women. Unborn children are particularly susceptible because CO has a longer duration for clearance in the foetal circulatory system and foetuses cannot compensate for a reduction in oxyhemoglobin without a sustained increase in cardiac output (7).

Factors affecting health effects

Together with CO₂, CO accounts for 90 per cent to 95 per cent of the carbon produced during the combustion of biomass (17). CO release correlates highly with the release of other compounds in smoke, including PM and formaldehyde. CO emission factors range from 60 g/kg to more than 300 g/kg of fuel consumed. Studies indicate that CO emission factors in Brazil ranged from 167 g/kg to 209 g/kg, which is generally higher than similar measurements for logging slash fires in the western United States where the average emission factor is 171 g/kg. The differences are thought to result from variations in vegetation or moisture content.

Although one study indicates a significant increase in blood carboxyhemoglobin levels in non-smoking people who used biomass fuels for cooking (18), the factors that affect health effects have yet to be fully evaluated. According to the United States Occupational Safety and Health Administration (OSHA) regulations, the time-weighted average exposure limit is 50 parts per million (ppm) CO for an 8-hour work shift; the National Institute for Occupational Safety and Health limit is 35 ppm for 8 hours of exposure and 200 ppm for no defined time (5). Systematic studies of the effects of CO on human health should be performed, with carboxyhaemoglobin levels checked soon after exposure.
Aldehydes

Health effects

Aldehydes are primarily mucous membrane irritants. Some, such as formaldehyde, may be carcinogenic and in combination with other irritants may lead to an increase in the carcinogenicity of other compounds, such as PAHs (9). Formaldehyde and acrolein are the main aldehydes released during biomass burning. Formaldehyde, which is probably the most abundantly produced compound of this class, causes eye, nose, and throat irritation during smoke exposure (5). Low molecular weight aldehydes such as acrolein are thought to cause pulmonary lesions in rabbits (5).

Factors affecting health effects

These compounds have been poorly quantified as byproducts of the forest fuel combustion in the open environment. Sharkey (9) states that it is highly likely that acrolein is an irritant in smoke near firelines, with concentrations as high as 0.1 ppm to 10 ppm near fires.

Organic acids

Health effects

Organic acids, such as formic acid produced by the oxidation of formaldehyde, are known to form during the combustion of biomass fuels. Anticipated health effects include irritation of mucous membranes.

Factors affecting health effects

Organic acid production rates and combustion conditions, and the synergistic effects of some or all of these compounds, are unknown (9). It has been observed, however, that under equilibrium, high humidity could drive reactions to the production of organic acids. Aldehydes, for example, can produce acidic groups (e.g., formic acid, acetic acid) under conditions of high moisture.
Semivolatile and volatile organic compounds (VOCs)

Health effects

Some VOCs may cause skin and eye irritation, drowsiness, coughing and wheezing, while others (e.g., benzene and 1,3-butadiene) may be carcinogenic. Benzene and benzo(a)pyrene may be genotoxic carcinogens (7).

Factors affecting health effects

VOCs may have significant vapor pressures at ambient temperatures. Some compounds, such as benzene, naphthalene, and toluene, are partitioned between gaseous, liquid, or solid phases at ambient temperatures. Little work has been done to characterize VOCs in forest fires. To date, methane and CO gases are produced in proportion to semivolatile and VOCs and serve as indicators of their abundance (9).

Free radicals

Health effects

Free radicals are abundantly produced during the combustion of forest fuels. Free radicals may react with human tissues. They have been observed to persist up to 20 minutes following formation and pose a problem for firefighters exposed to fresh aerosols. Additional research is needed to determine the types and quantities of free radicals emitted during the combustion of biomass fuels, their persistence in the atmosphere, and subsequent health effects (9).

Factors affecting health effects

None noted at this time.
Ozone ($O_3$)

*Health effects*

$O_3$ is an extremely reactive oxidant. At high concentrations, it may impair lung function and reduce respiratory resistance to infectious diseases. People at risk include those with chronic respiratory illness. At low levels, human health may be affected when physical exercise is combined with several hours of exposure, i.e., tissue dose is enhanced by increased respiratory rate (7). At low concentrations, $O_3$ can cause symptoms such as coughing, choking, shortness of breath, excess sputum, throat tickle, raspy throat, nausea, and impaired lung function when exercising. Long-term health effects include decreased lung function and chronic obstructive pulmonary disease (7).

*Factors affecting health effects*

Concentrations of concern are not expected in areas close to fires. $O_3$ is formed photochemically near the top of smoke plumes under high sunlight. It is also formed when smoke is trapped in valleys or where there is a temperature inversion. Additionally, increased levels of $O_3$ may be encountered at high elevations.

OSHA has established standards for occupational exposure to $O_3$; however, these regulations have yet to be evaluated, along with other chemicals for biomass burning.

*Inorganic fraction of particles*

*Health effects*

Toxicologic effects of inorganic fractions from biomass fires have not been quantified. Health effects are dependent on the substance in question, such as lead, asbestos, and sulphur.

*Factors affecting health effects*

Inorganic materials, which are generally present in trace levels in smoke particles, are dependent on the chemistry of the fuels burned and the intensity at which the fire burns. Often, variability in the mineral content of fuels is enough to affect combustion. For example, in the United States,
particles in the Los Angeles Basin were found to have a higher lead content than particles from fires in the Pacific Northwest due to deposition of lead deposits in those areas (5). Similarly, asbestos fibers were carried with smoke from areas that naturally contained high deposits of asbestos (5). Also, organic soils of the southeast and fuels in the Yellowstone geyser basins would have emissions with sulphur-containing gases because they contain naturally occurring areas of high sulphur deposition (5).

Savannah fire aerosols are characterized by enrichments in elements such as potassium (K), chlorine (Cl), zinc (Zn), and bromine (Br), whereas forest fire emissions are enriched in silicon (Si) and calcium (Ca). Of the trace elements, K is found in relatively high concentrations in wood smoke. The combustion of hardwoods produces more ash and therefore higher concentrations of trace elements than does the combustion of softwoods (19).

**Trace gases and other releases**

*Health effects*

Trace gases, particularly polychlorinated dibenzo-p-dioxins (PCDDs), are extremely persistent and widely distributed in the environment. Very little human toxicity data related to PCDD are available. Data of health effects in occupational settings are based on exposure to chemicals contaminated with 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), which has a half-life of 7 to 11 years in humans. Dioxin exposures are associated with an increased risk of severe skin lesions (e.g., chloracne), and hyperpigmentation, altered liver function and lipid metabolism, general weakness associated with weight loss, changes in activities of various liver enzymes, immune system depression, and endocrine and nervous system abnormalities. TCDD also causes cancer of the liver and other organs in animals. Exposure to dioxin-contaminated chemicals has resulted in increased incidences of soft-tissue sarcoma and non-Hodgkin’s lymphoma (20).

Methyl bromide and methyl chloride, which are sources of Br and Cl that destroy stratospheric ozone (21), may be carcinogenic (22). Health effects resulting from the emission of these compounds from biomass fires have yet to be determined.
Factors affecting health effects

Smoke emitted during the global annual combustion of about 2 to 3 billion metric tons of plant materials contains numerous toxic materials, some of which are dioxins. Forest and brush fires are major sources of PCDDs (23, 24). If flame temperatures exceed 1000 °C, essentially no dioxins are produced; however, this is rarely the case. In a study that involved burning various wood specimens in different stoves, total dioxins released were as much as 160 µg dioxin/kg wood. Soot collected and analyzed by well-designed and documented procedures indicated the presence of tetrachlorinated, hexachlorinated, heptachlorinated, and octachlorinated dioxins (23, 24).

Wood combustion products are spread around the world by winds. Consequently, PCDDs are found in soils in remote areas and tend to be bioconcentrated in the food chain (23).

Biomass fires emit a complex mixture of particulates and gases into the atmosphere. Globally, the diversity of combustion products results from wide ranges in fuel types and fire behaviour, which are induced by large variations in ecological types and weather phenomena. For instance, forest fires have lower combustion efficiency than grass fires, and therefore a larger fraction of smouldering compounds. During less efficient smouldering combustion, a large number of organic compounds are formed (5).

Radionuclides and herbicides

Health effects

Radionuclides, such as iodine-129 (\(^{129}\)I), cesium-137 (\(^{137}\)Cs), and chlorine-36 (\(^{36}\)Cl), can be released into the atmosphere, soil, and water, with immediate and long term consequences on health (25). They can cause cancer, depending on where in the body they are localized. For example, iodine is concentrated in the thyroid gland and the radioactive isotopes can cause thyroid cancer.

Fire occurring immediately after the application of herbicides may lead to adverse health effects in forest workers; however, in one study, no herbicide residues from an application containing the active ingredients imazapyr, triclopyr, hexazinone, and piolaram were detected in 140 smoke samples and 14 fires (26).
Factors affecting health effects

Fires can mobilize radionuclides from contaminated biomass through suspension of gases and particles in the atmosphere or solubilization and enrichment of the ash. Loss to the atmosphere increased with fire temperature, and during a typical field fire, 80 per cent to 90 per cent of the I and Cl, and up to 40 per cent to 70 per cent of the Cs was lost to the atmosphere (25).

In assessing exposure, factors such as fire conditions (high density smoke versus low density smoke) and personnel location should be taken into consideration when assessing exposure to airborne herbicide residues in smoke from prescribed fires (26).

RADIATIVE EFFECTS THROUGH GLOBAL COOLING

Smoke particles affect the global radiation balance by reflecting solar radiation directly, acting as cloud condensation nuclei, and increasing cloud reflectivity. The radiative effects of aerosols generated from biomass burning, dust storms, and forest fires could increase global cooling (i.e., or reduce the rate of global warming). Anthropogenic increases of smoke emissions may help weaken the net greenhouse warming from anthropogenic trace gases (27).

The effect is measured by Direct Radiative Forcing (DRF), the perturbation in the energy balance of the earth-atmosphere system; positive and negative values indicate warming and cooling, respectively, of the troposphere. For comparison, the net incoming solar radiation at the top of the atmosphere is 342 watts per square meter (W/m²). Radiative forcing due to aerosols is comparable in magnitude to current anthropogenic greenhouse gas forcing but opposite in sign. The DRF due to long-lived greenhouse gases is $2.45 \pm 0.37$ W/m²; the global average of DRF due to anthropogenic aerosols is -0.5 W/m², largely attributed to sulphate particles from fossil fuel combustion and smoke particles from biomass burning (28).

Severe aerosol loading results in immediate health effects, specifically respiratory disease from particle inhalation. It also may lead to a reduction in photosynthesis, which may affect the incidence of infectious and mosquito-borne diseases in the long-term. In regions of intensive biomass
burning, the photosynthetically active spectrum of sunlight (wavelengths of 400-700 nanometers (nm)) is reduced by 35 per cent to 40 per cent for two months (27). In one study, smoke from biomass burning caused significant aerosol optical thickness and up to an 81 per cent reduction in ultraviolet-B (UV-B) rays (29).

UV-B in natural sunlight kills airborne bacteria (27). The bactericidal effects of solar UV-B are well-known, and significantly reduced UV-B resulting from severe air pollution in regions where UV-B levels are ordinarily high might enhance the survivability of pathogenic organisms in air and water and on surfaces exposed to sunlight. In one study, exposing drinking water to normal intensities of UV-B has reduced diarrhea in children in Kenya by 33 per cent (30).

An increased incidence of respiratory, cardiopulmonary and other diseases are known to be associated with severe air pollution, but the biological mechanisms remain unknown.

The increased incidence of infectious and mosquito-transmitted disease has been raised as a possible consequence of severe aerosol loading. The larvae and pupae of some disease-transmitting mosquitoes are highly photophobic to ultraviolet-A (UV-A) rays and green wavelengths of sunlight. In 1995, in Brazil, smoke reduced sunlight in UV-A (340 nm range) as much as 45 per cent in an area peripheral to the region of maximum burning (29). Experiments with Culex pipiens, a vector for encephalitis, indicated that the females deposited eggs in the darkest nurseries and that their larvae avoided UV light (27).

The biological aspects of severe aerosol loading require further investigation. Estimates of emission factors of pollutants from forest fires and biological mechanisms leading to adverse health effects will improve global accounting of radiation-absorbing gases and particles that may be contributing to climate change and will provide strategic data for fire management.
REFERENCES


