Human Health Impacts of Forest Fires in the Southern United States: A Literature Review[1]

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Abstract

Forestry management practices can shape patterns of health, illness, and disease. A primary goal for owners of federal, state, and private forests is to craft ecosystem management plans that simultaneously optimize forest health and human health. Fire—a major forest management issue in the United States—complicates these goals. Wildfires are natural phenomena with unpredictable effects. Controlled fires, on the other hand, are often prescribed to reduce biomass fuels, reduce wildfire risks, and protect resource values. While fires can enhance the health of fire-adapted ecosystems, research on the human health impacts of smoke from forest fires is somewhat equivocal. This article synthesizes 30 years of research on the human health impacts of forest fires. It summarizes our current state of knowledge about the following: biophysical effects of environmental contamination resulting from forest fires; psychosocial impacts of forest fires; occupational exposure issues among fire crew; visibility impairment from forest fire smoke; and health care measures that address the impacts of forest fires. This article provides information that may be useful for land managers, researchers, policy makers, health care workers, and the general public in decision-making about forest management practices. It also recommends that future research use integrative health models and adopt ethnographic research methods.

Fire Research in the South

Forestry management practices can shape patterns of health, illness, and disease. A primary goal for federal, state, and private foresters is to craft ecosystem management plans that simultaneously optimize forest health and human health. Fire complicates these goals. Fire is a major forest management issue in the United States because of its frequency and its potential to damage natural and human resources. Wildfires are natural phenomena with unpredictable effects that occur across the continent at varying rates. Controlled fires, on the other hand, are often prescribed to reduce biomass fuels, reduce wildfire risks, and protect resource values. It is common for people who own forests in fire-adapted ecosystems to use prescribed (or controlled) burning as a means for creating healthy forest ecosystems. Many ecosystems in the southern United States are fire-adapted; for example, evergreen shrub bogs, sand-pine scrub, and flatwoods on the Coastal Plain; prairie grass savannas and pine forests in the Piedmont; and Table Mountain pine (*Pinus pungens*) and pitch pine (*P. rigida*) forests in the southern Appalachians.

While fires can enhance the health of fire-adapted ecosystems, research on the human health impacts of smoke from forest fires is somewhat equivocal. The health risks of smoke are particularly relevant in the southern United States, the region with the highest annual average prescribed burn area in the United States (Haines et al. 1998). Between 1985 and 1994, 424,119 hectares were submitted to prescribed fires (Haines et al. 1998). For most people in the South, smoke produced from forest fires has very little or no health impact. However, smoke is a very real concern for certain

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segments of the population. Young children, the elderly, people with pre-existing cardiopulmonary and psychiatric conditions, and smokers are particularly vulnerable to smoke-related health risks. People at greater risk of exposure to smoke from forest fires, for example residents of wildland-urban interfaces, outdoor enthusiasts, and firefighters, are also more vulnerable to health risks.

This article synthesizes 30 years of research on the human health impacts of forest fires. Research on this topic is taking place in a variety of disciplines including forestry, pulmonary medicine, epidemiology, public health, clinical and animal toxicology, sociology, and anthropology. Epidemiologic studies on the health consequences of indoor air pollution created by the burning of biomass fuel for cooking, heating and light offer insight into the health impacts of biomass smoke created by forest fires (Larson and Koenig 1994). Studies in the field of animal toxicology provide information about the impacts of biomass smoke on the health of animals that can be extrapolated with caution to expand our knowledge of human health impacts. In animal toxicology studies of the effects of the smoke from burning pine on dogs, researchers observed changes in epithelial cells that predict the development of pulmonary hypertension which increases heart attack risks (Larson and Koenig 1994). Damages to tracheobronchial epithelial cells appear in rabbits that breathe smoke from burning white pine (Larson and Koenig 1994). Enzymatic changes predicting the development of pulmonary hypertension occurred in dogs that were forced to breathe highly concentrated smoke from burning pine (Larson and Koenig 1994). Significant changes in macrophages occurred in rabbits that were forced to breath smoke from burning Douglas fir (Larson and Koenig 1994). In the field of anthropology, researchers are interested in contemporary burning practices of communities around the world (e.g., Vayda 1999). Anthropologists of Native North America have reconstructed burning practices of prehistoric and early-historic communities within the context of overall ecological management regimes (e.g., Krech 1999). These are only a few examples of research in a variety of disciplines that relates to the issue of the human health impacts of forest fires.

I have organized the research into the following sections for this literature review:

- Health consequences of air pollution
- Health consequences of water contamination
- Psychosocial issues
- Occupational exposures
- Visibility impairment
- Health care measures

Variable Health Impacts

There are many factors that prohibit our ability to make generalizations about the ways that people experience forest fires. Variable factors such as fire behavior and fuel conditions—including types of biomass and moisture levels in the soil—mediate the human health effects of pollutants in biomass smoke. Fire intensity is another variable factor that influences the composition of biomass smoke. In higher intensity fires carbon dioxide and water are the principle emissions. But, lower intensity fires characterized by incomplete combustion, produce greater volumes of harmful gases including carbon monoxide, nitrogen oxides, sulfur oxides, hydrocarbons, polynuclear aromatic hydrocarbons, aldehydes, and free radicals.

Human biological and cultural diversity result in variable health impacts. Individual responses to biomass smoke are conditioned by personal biophysical histories (e.g., genotype), previous and current exposures to pollutants, and variable coping strategies (American Thoracic Society 2000). Some segments of the population present symptoms of smoke inhalation at dose-exposures that appear not to affect others or that have a very low impact on others (Evans and Campbell 1983; Therriault 2001). The groups who are particularly vulnerable to biomass smoke are young children, the elderly, people with pre-existing conditions, and smokers.

Weather also confounds relationships between biomass smoke and human health. For instance, wind patterns disperse smoke from a combustion site in irregular ways thus producing spatial variability in health impacts. The southern United States has particular meteorological traits (e.g., temperature, humidity) and ecological characteristics that dissuade researchers from using studies conducted in other

regions of the United States to design forest management plans and to assess human health impacts. Seasonal weather differences may affect health outcomes in the South differently than in other regions (Schwartz 1994). In all regions of the United States, respiratory problems are most common during the winter. In the South air pollution is at its worst during the summer while in the North air pollution is worse during the winter months. Some propose that air pollution does not complicate winter respiratory conditions in the South to the same degree as it does in other regions (Schwartz 1994). Others argue that regional differences in temperature and humidity do not affect patterns of respiratory illnesses associated with air pollution (Dockery and Pope 1994). This issue is one among numerous instances of the overall uncertainty in the research literature about the relationships between smoke and human health.

It is difficult to make general assessments of the health risks from biomass smoke as a whole. Information about the relation between human health and single constituents of biomass smoke is more abundant in the scientific literature than information about the health effects of some combination of constituents. Knowledge of the combined effects (additive, potentiated, and synergistic) of the multiple constituents of biomass smoke is limited because most research to date examines the effects of single constituents. Yet, people experience biomass smoke as a complex mixture of chemical compounds rather than as isolated components. Even if scientific case studies of the relation between human health and biomass smoke from particular forest fires were plentiful, generalizations could only be made with caution since the constituents of smoke and their relative proportions vary from one fire to the next.

Health Consequences of Air Pollution

It is unclear whether the net effects of forest fires to human health are adverse, beneficial, or inconsequential. Most investigations of this topic attempt to document adverse effects with little or no attention to beneficial effects. Yet, beneficial changes in interpersonal relations, and in socio-cultural, economic, and political systems can occur as a consequence of forest fires. Some researchers ask, "What are the harmful effects of *x* constituent of biomass smoke?" or "How did *y* fire impact the health of local people?" If they have not been able to demonstrate significant negative impacts, researchers conclude that the effects of forest fires are inconsequential. This section focuses on research that demonstrates the *adverse* biophysical effects of biomass smoke since the larger portion of researchers approach the topic from this angle.

Forest fires produce biomass smoke containing a range of pollutants. Under some conditions and in certain concentrations, biomass smoke can adversely affect human health. Adverse effects of biomass smoke are defined as medically significant or culturally recognized psychosocial and biophysical changes in individual or population health (American Thoracic Society 2000). At lower concentrations smoke may not directly threaten biophysical health, but can nevertheless be a "nuisance" (Machlis 2002).

Inhalation, ingestion, and dermal absorption are the routes of exposure to smoke pollutants. Inhalation is the most common pathway through which humans absorb constituents of biomass smoke. Dermal absorption might also occur through a person's surface cells. One substance that skin cells directly absorb is free radicals that may contribute to the development of emphysema, Adult/Acute Respiratory Distress Syndrome (ARDS), and lung cancer (Dost 1991). Gastrointestinal absorption is another pathway of exposure to the pollutants emitted by forest fires. Gastrointestinal absorption can occur through the ingestion of products such as plants that have absorbed pollutants through the soil or ash, wildlife that have inhaled or ingested pollutants, and freshwater species such as fish that have absorbed or ingested contaminated water.

Medically significant biophysical effects of biomass smoke include acute, subchronic, and chronic effects on public health. The spectrum of adverse physiological effects ranges from temporary, relatively minor eye, nose, and throat irritations, to persistent cardiopulmonary conditions, and less-commonly, to premature death. The most notable subset of biophysical effects involves cardiopulmonary functioning. It is clear that air pollution in general interferes with heart and lung processes. Changes in heart and

lung processes caused by biomass smoke as one specific type of air pollution are not as clear. In the following section, I discuss studies conducted on people who were exposed to biomass smoke as well as studies on the health effects of particular constituents of smoke. This research is helpful in our attempts to assess the cardiopulmonary effects of forest fires.

Cardiopulmonary Conditions Caused by Biomass Smoke

Respiratory conditions that result from inhalation of biomass smoke include temporary, permanent, and progressive respiratory dysfunction (American Thoracic Society 2000). Long-term exposure to smoke may increase risks of developing chronic illnesses such as cancer (Therriault 2001), and respiratory and vascular disease (Goh et al. 1999; Tan et al. 2000). The most notable cardiopulmonary problems resulting from biomass smoke (Betchley et al. 1997; Kane and Alarie 1977; Patz et al. 2000; Tan et al. 2000) are included in Table 1.

Table 1. The most notable cardiopulmonary problems resulting from biomass smoke (Betchley et al. 1997; Kane and Alarie 1977; Patz et al. 2000; Tan et al. 2000).

Decline in lung functioning
Decline in breathing rate
Breathing discomfort
Emphysema
Asthma
Allergies
Bronchitis
Angina
Myocardial infarction/heart attack
Pneumonia

Particulate Matter

Particulate matter[3] is one of the most significant emissions from forest fires. Ninety percent of particulate matter in biomass smoke is PM_{10}, meaning that it is 10 micrometers or smaller in diameter (EPA 1998; Ottmar 2001). Seventy to ninety percent of particulate matter in smoke is $PM_{2.5}$, meaning that it is 2.5 microns or smaller in diameter. Particles that have a diameter larger than 5 micrometers penetrate the upper respiratory tract. Particles with a diameter of 5 micrometers or less can penetrate the lower respiratory tract and deposit in the bronchioles and alveoli (Dockery and Pope 1994).

People who inhale particulate matter present respiratory symptoms such as coughing, wheezing, excess phlegm production, lung inflammation, systemic inflammation in the body, discomfort from breathing, and shortness of breath. Cough is the most common respiratory symptom associated with exposure to ambient particulate matter (Dockery and Pope 1994). The inhalation of particulate matter causes asthma, upper and lower respiratory tract infections, COPD (chronic obstructive pulmonary disease), and Ischemic Cardiomyopathy (Dost 1991 Eeden 2001; Health Research Working Group 2001 Larson and Koenig 1994). There is also a possible link between particulate matter and cancer (Adam et al. 2002).

Particulate matter aggravates pre-existing illnesses including asthma and heart conditions. People who have pre-existing conditions respond to lower dosages and shorter durations of exposure to biomass smoke than those who do not have pre-existing conditions. New cases of pulmonary diseases emerge when particulate matter occurs in the range of 10 100 m/m^3, while pre-existing cases were aggravated by the occurrence of particulate matter in the range of 20-40 m/m^3 for $PM_{2.5}$ and 40-50 m/m^3 for PM (Osterman and Brauer 2000).

[3] Particulate matter refers to particles that are present in the air. Particulate matter takes the form of smoke, soot, dirt, dust, and liquid droplets. Some sources of particulate matter are agricultural tilling, automobiles, factories, and driving on dirt roads. Particulate matter occurs in a range of sizes from coarse to fine. Fine particulate matter is especially threatening to human health because it can enter the respiratory system. The abbreviation for particulate matter is PM. The numbers that occur as subscript after PM refer to the size of particles. Thus, $PM_{2.5}$ refers to particulate matter that is 2.5 microns or smaller in diameter.

Some researchers document associations between elevated concentrations of biomass smoke and declining lung function by measuring Forced Expired Volume in one second (FEV_1), Forced Expired Volume in three-quarters of a second ($FEV_{.75}$), and forced vital capacity (FVC) (Dockery and Pope 1994). In a series of studies cited by Dockery and Pope (1994) lower respiratory symptoms increase 3.0% for each 10 m/m^3 increase in ambient PM_{10}. Lung function decreased by 0.15% as measured by FEV_1 and $FEV_{.75}$ with each 10 m/m^3 increase in PM_{10}.

Acute biomass smoke pollution and exposure to particulate matter are associated with hematologic changes in humans (Tan et al. 2000). The inhalation of biomass smoke reduces red blood cell levels and damages cellular membranes as indicated by increases in albumin and lactose dehydrogenase and depression of macrophage activity (Larson and Koenig 1994).

The deposition of PM_{10} and SO_2 in the respiratory system resulting from the inhalation of air pollutants stimulates bone marrow to release white blood cells. The bone marrow produces leukocytes, platelets, and proteins in response to the circulating cytokines, promoting systemic inflammation in the body, and contributing to the development of cardiopulmonary disease (Eeden 2001). Cytokine production by alveolar macrophages in the lungs increases in association with increases in PM_{10} (Eeden 2001) indicating an increase in PMN band cells. Whereas PM_{10} immediately stimulates bone marrow to release PMN band cells, the stimulation provoked by SO_2 is delayed. PMN, polymorphonuclear leukocytes, are small white blood cells that specialize in phagocytosis, or the breaking down of cells for defense.

Irritants

Biomass smoke and some of its constituents are irritants. Smoke inhalation causes eye irritations and upper respiratory tract irritations. Symptoms from acute exposure to organic acids, aldehydes (e.g., acrolein and formaldehyde), and respirable particulate matter include teary and burning eyes, runny nose, and scratchy and sore throat. Sulfur dioxide by itself irritates the lungs and in combination with particulate matter has even greater irritating effects (Evans and Campbell 1983). Acrolein is an irritant that can cause cellular toxicity in the upper respiratory tract and ciliary stasis (Dost 1991). When forest fires burn in areas where the soil contains crystalline silica, smoke inhalation can cause silicosis, inflaming and scarring the lungs, thereby reducing oxygenation (Ottmar and Reinhardt 2001).

The inhalation of numerous plant compounds can cause skin and respiratory irritations. Some botanical species that cause skin irritations in people who have direct contact with the whole plant can cause even worse reactions in people who inhale the smoke that is emitted from the burning plant. One example of this sort is poison ivy (*Toxicodendron radicans*). Other plants that do not necessarily cause adverse reactions in their whole, living form may have severe consequences for people who inhale the smoke from the burning plant. An example of this sort is mountain laurel (*Kalmia* spp.).

Carbon Monoxide

Carbon monoxide is a major constituent of biomass smoke. Inhalation of carbon monoxide increases production of carboxyhemoglobin (COHb) above the body's normal amounts. Carboxyhemoglobin are bonds of carbon monoxide bonds and hemoglobin that form when carbon monoxide displaces blood oxygen. In excessive amounts, carboxyhemoglobin causes oxygen deprivation, damages body tissues, and induces coughing and cold-like symptoms (Evans and Campbell 1983; Therriault 2001). Carboxyhemoglobin also complicates atherosclerosis and coronary heart disease (Evans and Kantrowitz 2002; Ward et al. 1989).

There is an association between biomass smoke and chest pain. In 1998, Floridians who were exposed to smoke from forest fires developed chest pain and bronchitis (Patz et al. 2000). Ozone, a secondary product of biomass combustion, causes chest pain and other respiratory problems such as pulmonary edema. Additional responses to ozone exposure include headaches, and the aggravation of pre-existing asthma and pre-existing arrythmia (Evans and Campbell 1983; Patz et al. 2000).

Documenting Associations between Biomass Smoke and Cardiopulmonary Conditions

Researchers have documented associations between elevated air pollution and decreases in pulmonary functioning indicated by reductions in FEV and FVC (Larson and Koenig 1994). For instance, decreases in FEV_1 and $FEV_{.75}$ among school children in Steubenville, Ohio and the Netherlands are associated with increases in PM_{10} concentrations in the air (Dockery and Pope 1994). Asthmatic children in Birmingham experienced a decline in lung functioning associated with increases in PM_{10}: their FEV_1 was two orders of magnitude more than non-asthmatic children (Schwartz et al. 1993).

Another method for investigating smoke-cardiopulmonary linkages is by conducting surveys of the use of medical facilities in communities near forest fire events. These surveys demonstrate that hospital admissions and emergency room visits typically rise in communities that have been exposed to wood smoke. Patients in these communities present generalized respiratory symptoms, acute bronchitis, chronic obstructive pulmonary disease, asthma, and chest pain (Mott 1999; Schwartz et al. 1993). Associations also exist between ozone increases and hospital admissions, as well as between daily mortality and increases in particulate matter. The association between acute asthma and biomass smoke is not entirely consistent. A study in Australia found no increase in hospital admissions for acute asthma in association with bushfires (Cooper et al. 1994).

A survey by Mott (1999) found that, following a 1999 wildfire on Hoopa Valley National Indian Reservation, there was a 52% increase in visits to medical care facilities by reservation residents. Sixty three percent of interviewees in the study experienced lower respiratory tract symptoms while the biomass smoke was present. More than 20% of survey participants were still experiencing increased respiratory symptoms two weeks after the smoke levels subsided. People who had pre-existing cardiopulmonary problems (31.8% of the survey population) reported more respiratory symptoms than those who did not have pre-existing conditions.

Children and the elderly appear to be particularly sensitive to biomass smoke. Hospital admissions among the elderly for pneumonia and COPD increase in association with increases in PM_{10} (Schwartz 1994). A study in Birmingham, Alabama documented a lagged association of one day between increases in PM_{10} and increases in hospital admissions of elderly people for pneumonia and COPD (Schwartz 1994). Children with and without pre-existing asthma conditions experience more respiratory symptoms when ambient particulate matter and ozone concentrations increase (Schwartz 1994). Following exposure to air pollution caused by burning wood, children aged 1-5 years old experience lung dysfunction sooner than people of other ages (Ostermann and Brauer 2000).

Carcinogenesis

A number of the individual constituents of forest fire smoke exhibit carcinogenic effects in clinical trials. The results of pure trials may be misleading, though, since many substances covary with other substances and have emergent properties. An additional complication is the difficultly of replicating dose-exposures for individuals in a diverse population and for variable fire events (Evans and Campbell 1983). A great deal of research has been conducted on the constituents of air pollution. A portion of this research focuses specifically on the constituents of biomass smoke while other research concerns air pollution more generally. The following discussion of cancer-causing pollutants reviews literature addressing biomass smoke in particular. But in some cases, the authors of this literature draw from research on air pollution from sources other than forest fires.

The inhalation of air pollution containing particulate matter may cause lung cancer (Osterman and Brauer 2000). Inhalation of particulate matter contaminated with dioxins may have carcinogenic effects. For example, the dioxin TCDD–a component of an herbicide used in forestry management–sometimes occurs in biomass smoke (Mukerjee 1997). Sarcoma, non-Hodgkin's lymphoma, and liver cancer are associated with some of the trace gases that are present in biomass smoke including dioxins and methyl bromide (Mukerjee 1997). Clinical trials associate nitrogen oxides with increased cancer rates (Adami et al. 2002). Ozone—

produced from the hydrocarbons and nitrogen oxides emitted by fires—is carcinogenic.

Clinical trials have demonstrated the carcinogenic effects of over thirty polynuclear aromatic hydrocarbons (PAHs) and hundreds of PAH derivatives (Fang et al. 1999). High dose-exposures of some PAHs increase the risk of bladder cancer and lung cancer (Adami et al. 2002). When present, formaldehyde exacerbates the carcinogenic effects of PAHs. Nasal and nasopharyngeal cancer may be a long-term effect of formaldehyde inhalation (Therriault 2001; Ottmar and Reinhardt 2001). Formaldehyde may decrease sensory capacity. Other aldehydes, elemental carbon, and trace metals have potential carcinogenic effects (Partanen 1993). In small and infrequent doses, however, aldehydes may not produce a carcinogenic effect (Dost 1991). Aldehydes can also cause contact dermatitis and uticaria (Dost 1991). An association between sulfates, which are commonly present in biomass smoke, and cancer has not been established (Adami et al. 2002). Free radicals in forest fire smoke react with tissues indicating that they are carcinogenic and mutagenic.

Experimental field and laboratory burns show that forest fires could increase the risk of human exposure to the radionuclides iodine-129, cesium-137, and chlorine-36 in areas contaminated with radioactive elements (Amiro et al. 1996). Human exposure may occur through inhalation of smoke containing radionuclides or ingestion of plants growing in soil and ash containing radionuclides. In these cases, radionuclides can have immediate and/or delayed carcinogenic effects for the exposed population. Some researchers speculate that the wildland fire that burned through the Idaho National Engineering and Environmental Laboratory in 2000 may have exposed people in Idaho to harmful byproducts from the combustion of radioactive substances (Machlis 2002).

Premature Death

Loss of life may be an effect of biomass smoke (Goh et al. 1999). Premature death is an acute and chronic effect of the inhalation of particulate matter (Patz et al. 2000). Research shows an association between exposure to PM_{10} and premature death due to cardiopulmonary dysfunction (Brauer 1999; Core and Petersen 2001; Dockery and Pope 1994). People who live in areas with high levels of ambient particulate matter from biomass burning have reduced life expectancy (Brauer 1999). Some of the measures that researchers use to investigate the association between air pollution and morbidity and mortality are hospital admissions, visits to emergency room departments, visits to physician's offices, and use of medications such as bronchodilators for asthmatics (Dockery and Pope 1994). In addition, the reductions in FEV_1, $FEV_{0.75}$, and FVC that accompany increases in air pollution are predictors of premature death (American Thoracic Society 2000).

Dockery and Pope (1994:128) provide three explanations for the link between premature death and particulate matter: 1) "acute bronchitis and bronchiolitis may be misdiagnosed as pulmonary edema;" 2) "air pollutants may increase lung permeability and precipitate pulmonary edema in people with myocardial damage and increased left atrial pressure;" and 3) "bronchiolitis or pneumonia induced by air pollution, in the presence of pre-existing heart disease, might precipitate congestive heart failure."

While the statistically significant links between air pollution and premature deaths due to cardiopulmonary problems are well documented, the details of the causal links are difficult to explain. Dockery and Pope (1994) suggest that particulate matter is an additional environmental stressor that promotes premature death for vulnerable people and those who have pre-existing health problems. Particulate matter in urban and indoor air pollution causes respiratory illness and disease leading to premature death in infants, the elderly, and people with pre-existing cardiopulmonary disorders (Brauer 1999).

Acute exposure to carbon monoxide in doses high enough to dramatically reduce blood oxygen is deadly (Therriault 2001). Thus, carboxyhemoglobin can cause premature death. Carbon monoxide poisoning may cause atheriosclerotic disease leading to premature death (Evans and Campbell 1983). Some studies show that diseases result from interactions of carbon monoxide with nitrogen oxides and sulfur oxides (Evans and Campbell 1983). Most studies of

the association between particulate matter and premature death eliminated sulfur dioxide as a confounding pollutant (Fairley 1990; Pope et al. 1992). Other researchers suggest that long term exposures to particulate matter and sulfur dioxide emitted from biomass burning is suspected of causing pulmonary lesions that result in premature deaths due to cardiopulmonary failure (Tan et al. 2000).

Numerous studies document an association between abrupt, tremendous increases in particulate matter and increases in daily mortality, such as occurred in London in 1952 and in Donora, Pennsylvania in 1948 (Schwartz 1993). Acute exposure to less dramatic increases in PM_{10} have been associated with increases in mortality in Birmingham, Alabama and eastern Tennessee, as well as in other regions of the United States (Schwartz 1993).

Dockery and Pope (1994) cite a set of studies that document a consistent correlation between increases in PM_{10} and increases in daily mortality. In a study in Kingston, Tennessee researchers found that for each 10 m/m^3 increase in PM_{10} there is a 1.6% change in daily mortality. In Birmingham, Alabama researchers documented a 1.0% change in total daily mortality for each 10 m/m^3 increase in PM_{10}; including a 1.5% change in respiratory mortality and a 1.6% change in cardiovascular mortality. A lagged association appears in which daily mortality correlates to increases in PM_{10} between one and five days prior to the day that the increases in mortality occur. Also notable in the studies cited by Dockery and Pope (1994) is the association between each 10 m/m^3 increase in PM_{10} and an 0.8% rise in the numbers of patients admitted to hospitals and a 1.0% rise in the number of patients who sought emergency care. There was a 3.4% increase for each 10 m/m^3 increase in PM_{10} in asthmatic patients who sought emergency care. Among asthmatics there was a 3% increase in both asthmatic attacks and bronchodilator use. Deaths due to cancer and other non-cardiopulmonary issues were not associated with rises in PM_{10} in any of the studies cited by Dockery and Pope (1994).

Forest fires are also linked to deaths from heart attacks. In 1998 a firefighter from the Alabama Forestry Commission was constructing a fireline when he had a fatal heart attack. Three heart attack deaths among the general public were connected to the 1998 Florida forest fires (Wade 1998).

Other Adverse Health Effects of Biomass Smoke

Biomass smoke is the source of several other types of adverse health impacts. These include suppressed immunity, physical and cognitive impairments, and direct injury. Very little research has been conducted on these topics, which is reflected in the brief discussion that follows.

Suppressed Immunity

The inhalation of wood smoke decreases resistance to lung infections and increases susceptibility to respiratory infections by interfering with macrophage phagocytosis (Brauer 1999; Dost 1991; Ward 1999). Aldehydes—namely acrolein—in wood smoke inhibit the ability of scavenger cells in the lungs to kill bacteria, thus increasing the possibility of respiratory infection (Ward 1999). The dioxins that are sometimes present in forest fire smoke are immunosuppressants (Mukerjee 1997). Dioxins increase susceptibility to infections (for example *Staphylococcus aureus*) by inhibiting humoral immunity and by affecting T-lymphocytes and B-lymphocytes (Mukerjee 1997).

Physical and Cognitive Impairments

Trace gases in air pollution are associated with weight loss, weakness, and fatigue. Carboxyhemoglobin, from breathing excessive amounts of carbon monoxide, causes deficiency of blood oxygen leading to slower reaction times, slower reflexes, drowsiness, disorientation, fatigue, diminished work capacity, reduced manual skills, and impaired mental abilities (Betchley et al. 1997; Evans and Campbell 1983). Inhalation of excessive amounts of carbon monoxide reduces maximal aerobic capacity but not submaximal capacity in "young, healthy males" (Evans and Campbell 1983:148). The physical discomforts and psychological stress that accompany exposure to forest fire smoke may also be a causal factor in decreased performance (Evans and Campbell 1983). Air pollution causes an assortment of other physical and cognitive impairments including the following: inability to distinguish letters, colors, and brightness;

inability to calculate time intervals; and interference with peripheral vision and ability to respond to peripheral stimuli (Evans and Campbell 1983).

Direct Injuries

Forest fires cause an assortment of direct injuries (Patz et al. 2000). In the Baldwin Hills fire in Los Angeles, 12% of the community suffered burns and other physical injuries due to exposure to the fire including one woman who had burns on more than 60% of her body (Maida et al. 1989). An additional 12% of people in the community experienced a fall due to the fire.

Health Consequences of Water Contamination

The effects of forest fires on water quality vary due to differing characteristics of the particular fire and the environment in which it occurs. Slope, ground cover, precipitation, and temperature all influence the water quality changes that occur in burned areas. In addition, fire intensity and severity, and post-burn treatments affect water quality. Fire severity—as a measurement of the amount of fuels burned and nutrients released—is particularly influential on water quality changes. The potential for erosion rises in association with fire severity: more severe fires cause more dramatic changes in ground cover (Landsberg and Tiedemann 2000).

In some ecosystems, forest fires threaten water quality through several pathways. For instance, forest fires that burn riparian vegetation can increase erosion that, in turn, can increase the frequency of flooding. As a result of erosion, excess sediment and nutrients (e.g., nitrates and nitrites) are deposited in water sources (Landsberg and Tiedemann 2000). Thus, turbidity in streamflow often increases after a forest fire. Turbidity poses indirect threats to human health by encouraging microbial production and increasing the risks of contracting infections for people who come in contact with untreated water. Excessive amounts of sediment in a water supply may stress filtration systems at water treatment facilities (Machlis 2002). The potential declines in water quality that sometimes accompany forest fires pose risks to human health.

In addition to the erosion of sediment, the direct diffusion of biomass smoke into surface water is a source of nitrogen in water sources (Landsberg and Tiedemann 2000). Similarly, excess phosphorous partly results from the leaching of ashes that drop and dissolve directly in streamwater (Landsberg and Tiedemann 2000). Mercury, a toxic metal that is a powerful neurotoxin (Tonnassen 2000), is sometimes present in forest fire smoke and may be deposited in water supplies. Human exposure to mercury can occur through ingestion of freshwater species and wildlife as well as through the inhalation of biomass smoke. It has been suggested that forest fires increase the concentration of dissolved salts in drinking water, but this has not been adequately demonstrated (Van Lear and Waldrop 1989).

In some situations, the exposure of surface waters to sunlight may decrease, such as when biomass smoke and haze block ultraviolet light (UV-B). The risk to human health occurs when a reduction in UV-B is sufficient enough to increase the growth of bacteria and pathogens in water supplies (Malilay 1999). In other situations, forest fires increase the exposure of surface waters to sunlight. Water temperatures may increase when fires burn off riparian vegetation exposing water sources to more direct sunlight. Eutrophication, affecting the "color, smell, and taste of drinking water" (Landsberg and Tiedemann 2000:128), results from increased water temperatures (Amaranthus and Arthur 1988).

Fire suppression and control techniques potentially damage water quality (Landsberg and Tiedemann 2000; Norris and Webb 1988). For instance, the harmful chemicals (e.g., nitrates and ammonia) that are found in the retardants and foams that are used in fire suppression may wash into water supplies. The construction of fire breaks or firelines may cause the erosion of nutrients into water supplies. Post-treatment techniques, such as the application of nitrate fertilizers to encourage the regrowth of vegetation, may increase the potential for human exposure to toxic substances that are washed into drinking water supplies.

Relative to other forest management techniques, prescribed fires have less effect on water quality.

Following a prescribed burn in a loblolly pine forest in the upper Piedmont of South Carolina, a 0.05 parts per million (ppm) nitrate-nitrogen concentration was measured in nearby water sources (Douglass and Van Lear 1983). Nitrate-nitrogen concentrations were also found to be 0.05 ppm in the nearby water sources following post-treatment. Following post-burn treatments of a pine forest where a prescribed fire occurred in the coastal plain of South Carolina, 0.02 ppm nitrate-nitrogen concentrations were measured in water sources (Richter et al. 1982). Studies from the piedmont of Georgia demonstrated that prescribed fire did not have a significant effect on soil hydrology or suspended sediment concentrations in streamflow (Van Lear and Waldrop 1989).

Some of the declines in water quality associated with forest fires result from natural phenomena while others result from human actions. Soil erosion, sedimentation, diffusion, nutrification, and turbidity are consequences of forest fires. These consequences threaten human health by introducing bacteria, pathogens, and toxins into drinking water supplies. To some degree these consequences cannot be prevented since wildfires are unpredictable and difficult to control. Research shows that prescribed fires have much less effect on water quality than wildfires. Increasing the frequency of prescribed fires reduces the frequency and severity of wildfires. Thus, one way to lessen the impact that forest fires have on water quality is to increase the use of prescribed fires.

Up to this point, this article has discussed links between forest fires, the environment, and human health. The larger portion of research literature focuses on the biophysical effects of forest fires. Reports on studies of other types of health—namely, psychosocial health—outcomes are sparse. This is unfortunate since biophysical and psychological wellbeing are connected in multiple, complex ways. A more thorough understanding of the psychosocial implications of forest fires would enable fire crews, medical personnel, and relief workers in governmental and non-governmental agencies to better assist victims of wildfires. In regard to prescribed fires, a more comprehensive biopsychosocial perspective (e.g., Jones et al. 2002; Zimmermann and Tansella 1996) would also equip forest managers who implement prescribed fire with better tools for designing successful education and public relations programs.

Psychosocial Consequences of Forest Fires

Having acknowledged the need for a more integrative model of human health and the paucity of research on the psychosocial impacts of forest fires, I now turn to the literature on the topic. Literature that focuses specifically on forest fires as well as research that addresses more generalized phenomena such as air pollution and natural disasters are included. This discussion is much more applicable to understanding the relationship between human health and wildfires rather than prescribed fires. While I do mention several links between prescribed fires and psychosocial wellbeing, comparatively little information is available on this topic.

Exposure to forest fires impacts psychosocial wellbeing in a variety of ways (Evans and Kantrowitz 2002). The spectrum of medically significant psychosocial effects ranges from temporary frustration, to temporary or permanent reduction of health-related quality of life (HRQL), to post traumatic stress disorder (PTSD). Beneficial psychosocial consequences of forest fires include positive transformations in interpersonal relations, financial profit, and community cooperation.

Forest fires have different effects on different communities: all communities do not respond to forest fires in exactly the same way. Likewise, forest fires have different effects on different individuals: within a community different individuals have different responses. Psychosocial effects may vary in association with the behavior and characteristics of particular forest fires. Psychosocial outcomes also vary according to an individual's experiences, perceptions, interpretations, and coping mechanisms. An individual's personal relationships and social contexts have a great influence on his/her attitudes and behaviors related to forest fires. It is possible that ethnicity influences psychosocial symptoms and minorities may be more vulnerable to psychological distress. For example, Mexican-American children when compared to children of any other ethnic groups developed clinical PTSD following a fire disaster investigated by Jones (2002).

Socio-cultural Transformations

Forest fires have been referred to as "engines of change" (Force et al. 2000) in communities. In a broader context, natural disasters have spawned social transformations monumental enough to be labeled "cultural evolution" (Oliver-Smith 1996:312).

Oliver-Smith (1996:302) describes disasters as "challenges to the structure and organization of a society." Forest fires may change community infrastructure (Machlis 2002). Interruptions in social services and damage to infrastructure cause individual and group stress (Oliver-Smith 1996). There may be significant changes in social structure as a result of forest fires. Individuals who experience a rise in social status may benefit from forest fires; for instance, community members who successfully control part of a wildfire or firefighters who keep a fire from damaging local structures. Other members of the community may not benefit from social changes. In some communities forest fires confer a negative image upon, or stigmatize, a particular place, person, or subgroup of the population (Machlis 2002).

Changes may occur in relations between communities and between cultural or ethnic groups (Gordon et al. 1995). Relationships may change between individual citizens, subgroups within a population, and between citizens and organizations (e.g., land and fire management teams). Social relationships and communication patterns within communities may change during and after a forest fire (Machlis 2002).

Researchers have found that natural disasters change political dynamics in communities (Oliver-Smith 1996). We might extrapolate from those studies to suggest that catastrophic forest fires—as a type of disaster—create conditions that encourage the reorganization of power relations, the formation of new alliances and agendas, and the emergence of activism (Oliver-Smith 1996). The politics of representation are a critical factor for communities experiencing forest fires. The power to portray forest fires and to represent the communities who experience fires influences perceptions held by insiders and outsiders to the community.

Natural disasters change the lived experiences of individuals and have the power to transform self-identity and community identity (Oliver-Smith 1996). Forest fires affect future perceptions and decisions related to self and community; for example, perceptions of forest fire risks and decisions about landscape management. Prescribed fires may positively affect aesthetic values leading to greater satisfaction with one's living environment. Severe wildland fires that cause more dramatic transformations of the landscape are more likely to be perceived as detrimental.

Perceptions of forest fires may change following a fire. Direct experience with a forest fire causes people to perceive that there is a higher risk of future fires or to become more fearful of fire (Machlis 2002). In some cases, prescribed fires may be less acceptable to people who previously had direct experience with fires (Machlis 2002). In other cases, people who experience a major fire near their home believe that the future possibility of another fire is very low (Cortner et al. 1990). If people live near fire-adapted ecosystems where fires "naturally" occur periodically, this belief may reflect a lack of knowledge about local fire regimes. Research shows that a forest fire can alter the future vulnerability and resiliency of a community (Machlis 2002) due to changes in ecosystem traits, material infrastructure, cultural characteristics, and social relations.

Significant religious changes may follow major disasters such as wildfires. Forest fires can also instigate changes in cultural values. For instance, values regarding marriage may shift from a view of it as a long-term commitment, to seeking marriage as an immediate means for gaining security (Oliver-Smith 1996). Transformations in symbols and rituals occur as a consequence of natural disasters (Oliver-Smith 1996). People may mourn for the symbols of self and community that are damaged or destroyed by natural disasters such as forest fires.

Grief and Distress

People exposed to forest fires may experience grief. Property loss, such as the destruction of a home or damage to personal goods, can be a source of grief. Feelings of helplessness may arise among people whose lives and property are threatened by wildland fires (Machlis 2002). Research on effects of natural disasters in general shows that damages

to meaningful places, such as homes, evoke emotions of grief (Oliver-Smith 1996). It is likely that people experience grief and a sense of loss when forest fires damage meaningful locations, gathering places, and other public spaces. In some cases fire, like other types of natural disasters, may cause the disruption of social contexts which is also a source of grief (Oliver-Smith 1996).

Air pollution is a source of psychological distress. Ozone—a component of air pollution—is associated with negative emotions and aggressive behaviors (Evans and Kantrowitz 2002). Studies show that the bad odors that often accompany air pollution episodes cause evaluative and cognitive deficiencies as well as behavioral disorders (Rotton 1983). Sensory stress from malodor impairs cognitive and intellectual functioning by interfering with an individual's ability to complete complex proof reading tasks, but does not decrease abilities to complete simple arithmetic tasks (Rotton 1983). One of the ways that sensory stress effects behavior is that when a person has little control, he/she becomes frustrated more easily (Rotton 1983).

Stress Disorders

Forest fires potentially induce more profound forms of stress and clinical illnesses (Jones 2002; Patz et al. 2000). For example, PTSD can occur among people who live in areas that have been affected by fires. Following a fire in 1985, members of the Baldwin Hills community in Los Angeles exhibited an array of post-traumatic stress symptoms (Maida 1989). In the community as a whole, 36% of people experienced PTSD symptoms. Among people who witnessed the fire 67% had trouble sleeping compared to 20% of people in the community as a whole. The PTSD symptoms exhibited by witnesses to the fire and the proportions of that population who experienced those symptoms include the following: 56% felt jumpy, 44% avoided reminders of the fire, and 33% had nightmares, dreams, and disturbing memories (Maida 1989). There was an increase in medical care and use of medication among witnesses to the fire. Most of the community members who lost property due to the fire exhibited symptoms of depression, with the exception of people who had good insurance and could replace their former home with a better, new home.

Destruction of 'place' is one of the traumas that evokes PTSD symptoms (Oliver-Smith 1996). PTSD symptoms emerge following dislocation. Similarly, the evacuations that occur when forest fires threaten homes and businesses or when biomass smoke reaches unhealthy levels (Mutch 2002; Therriault 2001; Wade 1998) create psychological distress. Although it has not been demonstrated in scientific studies, we might hypothesize that some portion of the thousands of people who were evacuated from their communities in Florida during the severe wildfire season in 1998 experienced some degree of psychological distress. Residents of Clancy, Montana who were being evacuated due to a forest fire experienced frustration, fatigue, stress, and panic (Machlis 2002). Other fire-related events that evoke PTSD symptoms in adults are threats to life, physical injury, and the injury or death of a loved one (Jones 2002).

Responding to and Recovering from Damages

Aid organizations can help mitigate psychological distress among people who have suffered injuries and loss due to forest fires. For example, Project Recovery provided emotional support for victims of the Cerro Grande fire in Los Alamos (Machlis 2002). On the other hand, the "strange people" in disaster relief organizations who enter a community to deliver aid or repair damage can be a source of stress for local residents (Oliver-Smith 1996). It is possible that fire management crews, like aid organizations, and the materials that they bring with them, cause stress for residents of communities located near fire events. The sights and sounds of equipment arriving to fight a fire may cause the recurrence of fear among people who have prior experiences with wildland fires (Machlis 2002). On the other hand, the influx of fire management crews into communities has the potential to generate revenue for the community as they purchase goods from local stores and patronize local businesses. Communities located near fire events may benefit from expanded employment opportunities created when fire management organizations move into an area and hire local people (Machlis 2002).

"Fire-adapted communities" (Burns 2003, personal communication) may be a useful concept for measuring a group's level of fire preparedness and capacity for coping with fires that do occur. Forest fires have the potential to galvanize or fragment communities. Cooperation among people can catalyze a community's recovery from disasters (Oliver-Smith 1996). For instance, joining together to rehabilitate land burned in a wildland fire had a healing effect for residents of Los Alamos (Machlis 2002). Social bonds may be strengthened among people who cooperate during a wildland fire and in preparation for or recovery from a wildland fire.

Communities who have low amounts of the kinds of capital (social, natural, and financial) useful for responding positively to fire events may have the highest risk of being adversely affected by forest fires. Newer communities, such as developments in wildland-urban interfaces composed of recent immigrants, may have less capacity to adjust after a fire because their social networks are less functional. In contrast, 'traditional' types of communities with strong, functional social networks may have more capacity to recover from a fire event (Burns 2003).

Strong social networks can serve as support systems helping individuals cope with the physical, psychological, and other effects of forest fires. On the other hand, weak or vulnerable social networks might create additional stress. Often, community members as well as local and extra-local organizations assist individuals with treating physical injuries and repairing material damages. Assistance with psychological issues may be an explicit target of aid or it may occur as a byproduct of other forms of assistance. Psychological issues are not, however, always recognized as a problem in need of attention.

To return to a previous point, it is crucial that fire and medical personnel recognize the interdependence of biophysical and psychosocial health. Psychology is a critical mediating factor for overall wellbeing. A finding that supports this proposition is that air pollution and malodorous air are associated with increases in depression and anxiety, and with increases in hospital admissions for psychiatric problems (American Thoracic Society 2000). A person's psychological condition can cause the biophysical effects of fire to be more or less severe (Evans and Campbell 1983). In the reverse flow of causality, a person may develop psychological problems such as depression or anxiety as a result of physical problems caused by forest fires (Evans and Campbell 1983).

Forest fires affect psychosocial health in multiple ways on both individual and community levels. Current research illustrates that forest fires have the power to transform a person or a community in ways that are beneficial and/or detrimental. Sometimes the changes are subtle and other times they are more evident. The spatial and temporal effects of forest fires can be far reaching, but they tend to be especially relevant for people located close to the place where burning occurs. Up to this point, discussion has focused on the ways that forest fires impact the general public; more specifically those members of the general public who are directly exposed to fire. The next section focuses on a special segment of the population whom researchers have studied more than any other community: fire workers.

Occupational Exposures

The experiences of fire workers differ from those of the general public. Two occupational factors that make fire workers a unique subgroup are their proximity to fire events and their dose-exposures to emissions from forest fires. An additional physiological factor that differentiates this group is that fire workers tend to be relatively physically fit. The general public and fire workers have similar responses to forest fires, but their dose-exposure patterns differ. Among the general public, adverse health effects appear in briefer time periods and at lower dosages (Brauer 1999; Ostermann and Brauer 2000).

Within the fire crew population, individual exposures differ according to the work practices of the particular firefighter (McMahon 1999), his/her location relative to the fire, and the amount of time he/she spends at that location. At a prescribed burn, variability in exposure to pollutants occurs within a group according to each person's particular duties. For instance, the "lighters" and "sawyers" have higher benzene exposures due to the use of gasoline in their drip torches and chainsaws. "Fireline holders" and "attack crew" have higher carbon

monoxide exposures due to their proximity to the flames and denser smoke.

Another work practice that varies among firefighters, influencing health risks, is shift duration. Wildland firefighters typically work shifts of eight to twelve hours or more. In some situations, wildland firefighters are at or near a burn site over a period of days or weeks where, even during their off-shift time, they are exposed to biomass smoke (Materna et al. 1992). In other situations, some portion of the work shift is spent in transit to and from the fire site and in other places some distance from the fire thus reducing the duration of a firefighter's exposure to biomass smoke (Reinhardt et al. 2000). Firefighters may be exposed to unsafe levels of pollutants for punctuated time periods, but not necessarily continuously for an entire work shift.

Variations in meteorological patterns, including wind speed and direction, can produce variable health impacts. High wind speeds keep smoke in the breathing zone of firefighters increasing their exposure to pollutants in biomass smoke (McMahon 1999). In these cases, firefighters are more likely to exceed occupational limits for the inhalation of carbon monoxide and respirable irritants such as particulate matter, acrolein, and formaldehyde (McMahon 1999).

Air Pollutants

In general, fire workers experience acute, subchronic, and chronic effects of exposure to forest fires. The acute exposures to respirable irritants that fire workers sometimes experience can result in runny noses, tearing eyes, stinging eyes and nose, and declines in lung function (Reinhardt et al. 2000). A study of Time Weighted Average (TWA) particulate matter exposures among wildland firefighters documented a high exposure of 37 mg/m^3 with a mean exposure of 9.5 mg/m^3 thereby exceeding the Occupational Safety and Health Administration-Permissable Exposure Limit (OSHA-PEL), which limits mean exposure to 15 mg/m^3 (Materna et al. 1999). A study of a "mop-up crew" at a forest fire found that 14% of exposures to total particulate matter exceeded the OSHA ceiling limit. Exposures to PAHs and crystalline silica among this crew were below OSHA-PELs. In some cases, the exposure of firefighters to PAHs may be consistent and long term, extending for several weeks while they are on duty (Rothman 1999). Chronic lung dysfunction among fire workers can occur as a result of the cumulative effects of exposures to smoke over longer time spans (Liu et al. 1992).

Exposure to unsafe levels of carbon monoxide from burning vegetation can cause fire workers to experience nausea, headaches, fatigue, impaired cognitive abilities, and reduced work capacity (Reinhardt et al. 2000). Research on fire worker exposures to carbon monoxide is equivocal on the issue of dose-exposures. Some studies found that fire workers' exposures to carbon monoxide during an 8-hour work shift did not exceed the OSHA-PEL of 35 ppm/hr (McMahon and Bush 1992). At wildfires, instantaneous carbon monoxide exposures of fireline crew have been measured to range from 3-80 ppm which is below the OSHA ceiling limit of 200 ppm. Other studies suggest that fire workers may be exposed to dangerous levels of carbon monoxide. For instance, a study of carbon monoxide concentrations near fire workers downwind from a North Carolina fire measured peak levels of carbon monoxide at 500 ppm with average exposures at 75 ppm (Brauer 1999). Other studies of wildland firefighers documented a risk for exceeding 5% carboxyhemoglobin, the National Institute of Occupational Safety and Health (NIOSH) recommended limit (Materna et al. 1992). The carbon monoxide exposures among gasoline pump operators at forest fires can reach as high as 300 ppm exceeding the OSHA ceiling limit (Materna et al. 1992).

In the Pacific Northwest, researchers measured 200 shift-exposures and burn-duration time-weighted-average exposures to pollutants among prescribed fire crews over a period of 3 years (Reinhardt et al. 2000). The exposure measurements were taken for a variety of fire workers including the "burn boss," lighting crew, holding crew, holding supervisor, attack crew, engine drivers and riders, sawyer, and "mop-up crew." Two percent of the group exceeded the American Council of Governmental and Industrial Hygienists-Threshold Limit Value (ACGIH-TLV) for carbon monoxide during

an eight-hour work shift. Eight percent exceeded carbon monoxide limits during a total burn (Reinhardt et al. 2000). For respirable irritants (formaldehyde, acrolein, and $PM_{3.5}$), 14% of shift-average exposures and 30% of exposures for the total burn exceeded ACGIH-TLVs. Thus, in some cases, firefighters may receive doses of particulate matter that are greater than OSHA-PELs (Liu et al. 1992).

Fire workers may be exposed to aldehydes at levels that exceed OSHA-PELs (Liu et al. 1992). Aldehydes that have been detected in biomass smoke include formaldehyde, acetaldehyde, furfural, and acrolein. One study found that biomass smoke contains more formaldehyde than any other aldehyde while another study found acrolein to be the most abundant of the aldehydes (Materna et al. 1992).

Studies of wildland firefighters have documented more adverse health effects of air pollutants compared to those among firefighters at prescribed burns. At the 1988 Yellowstone Fires, firefighters suffered declines in lung function indicated by decreases in FEV_1 and increases in methcholine responsiveness (Materna et al. 1992). Dust is the only air pollutant for which exposures among Yellowstone firefighters exceeded NIOSH occupational limits.

Psychological Stressors

Wildland firefighters, like other emergency workers, suffer numerous psychological stressors in addition to physical stressors. Fox and Bowlus (1996:42) list the following causes of stress among wildland firefighters: "line of duty death(s) or traumatic injury, severely injured or dead infants and children, very close calls that are particularly life threatening or emotionally upsetting, an incident attracting excessive media interest . . . a disaster . . . fire shelter deployment, burnovers, roll out of burning debris, and falling dead trees (snags)."

Fifty percent of 333 wildland firefighters reported experiencing 12 out of 45 stress symptoms (Table 2) listed on a questionnaire in the survey administered by Fox and Bowlus (1996). Table 3 includes strategies used by wildland firefighters to cope with stress.

Table 2. Main psychological stress symptoms of wildland firefighters and the percentage of respondents who experienced the symptom (Fox and Bowlus 1996).

76%	Frustration
69%	Irritability
63%	Anger
62%	Sadness
62%	Sleep disturbances
59%	Mood swings
56%	Avoidance of feelings
56%	Loss of enthusiasm
54%	Fatigue
56%	Relationship problems
53%	Anxiety
52%	Depression

Table 3. Wildland firefighters' coping strategies (Fox and Bowlus 1996:44-45).

91%	"concentrate on other things"
88%	exercise
88%	"think about how things could have been different if different actions would have been taken by the individual"
87%	"talk about the incident with coworkers"
86%	"talk with family and friends"
86%	"think about the humorous aspects of the event"
85%	"try to be more helpful to others"

The gender of the fire worker influenced stress experiences within the Fox and Bowlus (1996) survey population, with women experiencing emotional and acute physical stress more often than men. Ethnicity also influenced stress with Native American firefighters experiencing less stress than Caucasian and Asian firefighters. There were no significant differences in coping strategies between age groups, between women and men, or between ethnic groups.

Firefighter Safety

Firefighters as an occupational group encounter numerous injuries and deaths from a variety of causes. Several programs and organizations have been established to address firefighter safety. One example is the Fire Fighter Fatality and Investigation Program established by the National Institutes for Safety and Health in 1998 to understand and prevent firefighter injuries and deaths. Another example is the Federal Fire and Aviation Safety Team who, together with the National Interagency Fire Center, publishes "6 Minutes to Safety" (http://www.nifc.gov/sixminutes/index_j.asp), a web-based program whose objective is to educate firefighters in the most up-to-date safety initiatives. The National Interagency Fire Center maintains SAFENET (http://safenet.nifc.gov/), a system whose objective is to ensure firefighter safety by enabling all firefighters to report unsafe working conditions. The National Wildfire Coordinating Group (NWCG) provides safety training for firefighters and posts web-based safety alerts.

On the NWCG's website (http://www.nwcg.gov/teams/shwt/index2.htm), is a list of firefighter injuries and deaths from 1910-2002. Since 1910, 883 firefighters have died while on duty (Table 4).

Table 4. Numbers of firefighter fatalities for some of the main causes of accidents from 1910-2002 (source: National Wildfire Coordinating Group: http://www.nwcg.gov/teams/shwt/index2.htm).

Burnover	433
Heart attack	93
Aircraft accidents	47
Snag	32
Helicopter accidents	30
Airtanker accidents	25
Engine rollover	22
Burns	21
Dozer burnover	16
Electrocution	9

Direct Injuries

Firefighters sometimes become victims of unpredictable fire behavior. In 1999, two volunteer fire fighters died when they were overrun as they tried to flee upslope from a fire advancing through a hollow. A forest ranger died after receiving second and third degree burns over 60% of his body. He received burns while fleeing on foot from an advancing fire after a blade on his bulldozer got stuck in a tree.

Motor vehicle accidents cause deaths and injuries among both volunteer and career firefighters who are traveling to or from fire sites. The most common causes of death for career firefighters are asphyxiation and traumatic injuries not related to motor vehicles. The most common causes of death for volunteer fire fighters were asphyxiation and traumatic injury from accidents involving motor vehicles.

Contact with electrical currents caused 10 firefighter deaths between 1980 and 1999 according to the National Fire Protection Association. Some of the avenues through which fire fighters come into contact with electrical currents are: downed power lines; electrical currents transmitted through the ground; water application tools charged with electrical currents; electrically charged equipment and gear; and electrical currents conducted by smoke.

Other Health Effects

Deaths from heart attacks occur during fires. For example, in 1998 an Alabama Forestry Commission employee died of a heart attack while he was constructing a fireline (Wade 1998). In 2000, a driver/operator died from arrythmia brought on by atherosclerotic cardiovascular disease shortly after clearing debris from a fireline as part of the USDA Forest Service Wildland Fire Fighter "red card" certification program.

In their research, Spear and Cannell (2002) found that, among mixmasters whom they surveyed, exposures to respirable dust, dyes, and hydrogen cyanide in retardants never exceeded the limits dictated by ACGIH-TLV TWAs or OSHA-PEL TWAs. Mixmasters are the group of fire workers who prepare retardants that are used to control forest fires. Typcially, retardants are prepared by mixing water into powdered chemicals. Common fire suppressants

such as Fire-Trol GTS-R and Fire-Trol 300F contain potentially hazardous chemicals. These chemicals are effective fire suppressants, but are also potentially toxic to humans. Exposure to the ammonium sulfate in these retardants may cause "hypermotility, diarrhea, nausea, and vomiting from ingestion" (Spear and Cannell 2002:66). The diammonium phosphate in retardants may cause dermatitis, emphysema, asthma attacks, and irritations of the eyes, respiratory tract, and gastrointestinal tract. Long-term exposure to retardants may cause irritations to the eyes, skin, and respiratory tract.

Fire workers are exposed to variable levels of herbicides. Some studies revealed that forest workers are exposed to toxins from herbicides that were applied to forests immediately prior to burning (Malilay 1999). Other research demonstrated that the presence of herbicides from an application preceding a forest fire was not detectable in smoke (Malilay 1999).

Gharabegian et al. (1985) investigated noise exposures among several groups of fire workers including "fire line/camp crews," "helipad crews," and "ground crews" at an airbase. 100% of helipad crew members, 100% of portable pump operators, and 30% of those "hot shot crew" members who used chain saws received noise doses during a 14-hour work shift that exceeded OSHA allowable limits. However, among the fire line work group as a whole, only 10% of the members received a noise dose level above 100% of the OSHA allowable limits.

In sum, firefighters encounter unique health risks while performing their occupational duties. They are exposed to unusual concentrations of hazards and pollutants with atypical frequencies of exposure. Physical fitness, work practices, meteorology, and fire characteristics are some sources of variation in health outcomes among individual firefighters. Fortunately there are numerous safety programs and governmental regulations that minimize potential harmful consequences and protect the health of firefighters. Even though firefighters are typically the population most at risk, governmental agencies also maintain legal standards that protect the health of the general public from potentially threatening actions of forest fires such as the emission of air pollutants and the reduction of visibility on highways.

Visibility Impairment

The Environmental Protection Agency (EPA) considers visibility to be a matter of "public welfare" (EPA 1998). To protect public welfare, EPA has established primary and secondary National Ambient Air Quality Standards (NAAQS) with the goal of maintaining socially acceptable levels of visibility. The Interagency Monitoring of Protected Visual Environments (IMPROVE), a coalition of EPA employees and federal land managers, monitors and enforces compliance with NAAQS. NAAQS applies to the following six "criteria pollutants:" PM_{10} and $PM_{2.5}$ (fine particulate matter), ozone, nitrogen dioxide, carbon monoxide, sulfur dioxide, and lead (American Thoracic Society 2000). The American Council of Governmental and Industrial Hygienists (ACGIH), the National Institute of Occupational Safety and Health (NIOSH), and the Occupational Safety and Health Administration (OSHA) are three other organizations that maintain exposure limits and occupational standards for the pollutants that occur in biomass smoke. State, tribal, and local laws also contribute to the regulation of "nuisance smoke," a category that includes the smog that limits visibility. Resource management organizations, timber companies, and private landowners cooperate with governmental agencies in fire and smoke management activities (Mutch 2002).

The degree of visibility reduction in any area depends on the character and concentration of smoke emitted by a forest fire combined with meteorological factors such as humidity and wind patterns. Visibility decreases as humidity rates increase because more water is available for particulate matter to absorb which increases the ability of particulates to scatter light (EPA 1998). The high humidity that is typically found in many parts of the South results in more frequent nuisance smoke in this region than in some other regions of the United States. Achtemeier (2002:41) describes the complexity of the situation as follows: "Meterology, climate, and topography combine with population density and fire frequency to make nuisance smoke a chronic issue in the south."

The principle connection between visibility and human health is that the reduction of visibility due to forest fire smoke can cause highway motorvehicle accidents leading to injuries and fatalities (Goh et al. 1999). Detailed statistics are not readily available for the injuries and fatalities caused by visibility reduction. Some information is available, however. Between 1979 and 1988 there were more than 28 deaths, 60 serious injuries, and many minor injuries on roadways in the southern United States due to low visibility (Mobley 1990). In 2000, reduced visibility on highways caused by forest fire smoke resulted in 5 automobile deaths in Florida and 5 automobile deaths in Mississippi (Achtemeier 2002). In June 2000, a 14-mile section of Interstate 95 in Florida was closed when forest fire smoke reduced visibility to near zero and caused 5 traffic accidents in one morning (Machlis 2002).

"Super fog" is an extremely dense combination of smoke and water vapor that is emitted from smoldering fires and the burning of wet fuels (Achtemeier 2002). Super fog is very dangerous when motorvehicle drivers encounter it along roadways. A 2002 wildfire in south Florida produced super fog that caused a pileup with several fatalities on Interstate 75. Five people were killed and another 26 people were injured on the Mississippi/Alabama border in 2000 in an accident caused by super fog. People who encounter super fog while they are driving have a very difficult time navigating their vehicles because of the drastic reduction in visibility. Visibility can decrease to as little as three feet when super fog is present (Achtemeier 2002).

Another connection between visibility and human health is that forest fire smoke reduces the aesthetics of a vista which can have psychological consequences for people who value clear views. The cultural preference for scenic vistas that many Americans share is considered to be an Air Quality Related Value (AQRV) (Tonnassen 2000). The reductions in visibility that sometimes accompany biomass smoke can change the look of the landscape, typically in ways that do not coincide with human preferences. People have more appreciation for the beauty of landscapes when their views are unobstructed by smog (Machlis 2002).

Governmental regulations require fire personnel to maintain air quality and visibility. Fire workers are specifically trained to manage smoke so that the general public encounters minimal amounts. Researchers in the USDA Forest Service and other fire agencies devote a great deal of attention to understanding smoke and devising techniques to control it during wildfires and prescribed fires. Unfortunately, there are cases like the ones mentioned above where fire behavior, meteorology, and population patterns make this very difficult if not impossible.

Health Care Measures

Wildfire control and suppression techniques contribute to the reduction of human health costs. Prescribed fire practices are designed to produce minimal human health threats. The USDA Forest Service publishes smoke management guidelines that instruct land managers in the best ways to reduce the health costs of prescribed burns (Hardy et al. 2001). Numerous techniques are available to land and fire managers for preventing and reducing the potential for water pollution. For example, the Burn Area Emergency Rehabilitation (BAER) program includes treatments to prevent or reduce sedimentation of water sources in areas affected by wildfires (Landsberg and Tiedemann 2000). Workers at prescribed fires use techniques that protect water supplies including "limiting fire severity, avoiding burning on steep slopes, and limiting burning on sandy or potentially water repellent soils" (Landsberg and Tiedemann 2000:126).

Despite the best efforts of fire workers, biomass smoke sometimes reaches unhealthy levels in populated areas. Outdoor gatherings and activities should be curtailed during smoke episodes to decrease exposures to air pollutants. Exercising outdoors should be avoided where there are high levels of biomass smoke (Therriault 2001). Exercisers are vulnerable to higher doses of air pollutants because they tend to breathe through their mouth and to inhale faster and deeper bringing more pollutants into the lungs. Public health officials recommend that people stay indoors during smoke episodes either in clean air shelters or in homes with clean air (Therriault 2001).

Outdoor air pollution can penetrate indoor areas. To minimize indoor air pollution, avoid smoking tobacco and burning fossil fuels for heat, cooking, or light. A variety of air filters can be used to clean particulate matter and harmful gases from indoor air. One of the most effective home filters is the air conditioner. High Efficiency Particulate (HEPA) filters, and portable and electronic air cleaners are also recommended (Therriault 2001).

In some cases, it is necessary to evacuate people who live in an area where biomass smoke has reached unhealthy levels. Evacuation reduces exposure to harmful air pollutants by moving people from sites with high levels of pollution to locations with better air quality. Evacuation is feasible for some members of a community. But there may be socio-economic barriers that hinder some members from evacuating, such as job responsibilities and economic limitations (Mott 1999).

People who experience adverse health effects from air pollution seek care in hospital emergency rooms and are sometimes admitted to hospitals for respiratory (Patz et al. 2000) and other illnesses. Some people suffering from adverse consequences of biomass smoke seek care from private physicians.

One hypothetical method for reducing human health risks is to extinguish wildfires (Brauer 1999). In reality it is not possible to extinguish *all* wildfires and completely eliminate health risks. The complete elimination of forest fires as a source of air pollution is not an option. It is possible, however, to minimize air pollution and other health risks with appropriate management techniques.

Discussion

Opinions on the health impacts of forest fires are somewhat equivocal. Some researchers have found evidence that biomass smoke is injurious (Grant 1988), while others have found evidence that biomass smoke does not have significant adverse health effects (McMahon 1999; Van Lear and Waldrop 1989). Some researchers argue that public health risks from biomass smoke are minimal because air pollution stemming from forest fires rarely if ever exceeds limits set by governmental and non-governmental agencies (McMahon 1999). Other authors argue that serious damages to public health, including chronic disease and premature death, occur even when air pollution levels are below the limits set by governmental agencies (EPA 1998; Schwartz 1993).

The predominant view of fire ecologists and forest managers is that prescribed burning reduces long-term net health costs by reducing the risks of catastrophic wildfires that could result in even greater levels of air pollution and have other injurious effects. Fire ecologists promote prescribed burning as a technique for enhancing ecosystem health in fire-adapted areas that rely on periodic burnings. Many fire ecologists also promote a "let it burn" policy for wildfires arguing against the expensive policies designed to suppress or eliminate unplanned wildland fires. In this view, fire is regarded as beneficial for long-term ecosystem health and human health.

The ambiguity in the research literature on the health impacts of smoke is due both to the lack of and inherent difficulties with research on this topic. As previously mentioned, most research on smoke effects investigates single constituents of smoke such as aldehydes, PAHs, particulate matter, hydrocarbons, inorganic gases, and trace gases. Much of this research tests the effects of these pollutants on human health from sources other than forest fires such as automobiles and industrial production. Another deficiency of the research literature is that most studies look at short-term health outcomes, while very few studies of the long-term health effects of exposure to biomass smoke exist. Despite these limitations, our understanding of biomass smoke is increasing due to a growing interest in this subject among the general public, within the scientific community, and among policy makers and land managers.

Research on this topic should continue in order to fill some of the voids in existing knowledge. There is a need for more research that investigates individuals and communities in areas where forest fires burn. These studies ought to consider smoke as people actually encounter it during forest fires; that is, a whole, complex mixture of interacting chemicals and particles. Among the current literature, there is a striking lack of information about the perceptions of individuals. Future research on the health impacts of fire could be improved by using

ethnographic methods. Research would be much more textured if it included accounts of the ways that individuals interpret their experiences with forest fires.

Each facet of the health-fire relationship ought to be contextualized in a particular fire event and a particular environment. A theme that emerges from the literature reviewed in this article is the variability of health effects. Throughout the literature, researchers state that the degree to which fires impact air quality, water quality, and thus human health, vary depending on the particular fire's behavior, meteorological conditions, and human behavior. To be accurate, future research ought to coordinate the characteristics of particular fires with local environmental traits, in addition to local human conditions.

The inseparability of human health and ecosystem health in the context of forest fires is apparent in the research currently available. Yet, our present understanding is somewhat reductionistic and gives disproportionate attention to the physiological effects of fire. A more holistic view of the health impacts of forest fires would investigate psychological, social, cultural, economic, and political consequences as well. Future investigations should pay more attention to links between physiological and other types of effects of forest fires on people (e.g., psychological, economic, cultural). A holistic presentation requires both scaling up by contextualizing biomedical and chemical analyses and scaling down by adding fine-grained understandings of individuals' lived experiences. In sum, I suggest that in the future, researchers expand their methodological repertoire and use integrative models to better understand relationships between people and fire.

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