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Chapter 26

Integrating Research on Wildland Fires and Air Quality: Needs and Recommendations

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Abstract

A summary is presented that integrates general information on the causes and effects of wildland fires and emissions with various ecological impacts of forest fires and air pollution in forests and other ecosystems. We also synthesize information on the regional effects of wildland fires on ambient air quality in Europe, North America, Australia, and Asia, and how this may impact visibility and human health and security. In addition, advances in remote sensing (RS), modeling, and management of wildland fires and the resulting air pollution are summarized. We also provide information for researchers and managers on the most important needs and recommendations about the interactions of wildland fires and air pollution that have been discussed in this book.

26.1. Introduction

This book has presented a wide range of chapters focusing on the effects and interactions of wildland fires and air pollution and the implications of these factors for land and air resources managers. Information in the book is particularly important given the current research on carbon sequestration and carbon trading in terrestrial ecosystems in a changing climate. Regulators and land managers are increasingly interested in the effects of fire on residence time of carbon in forests and future management practices that could be used to improve long-term carbon

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storage on both public and private land. The use of prescribed fire as a management tool needs to be reevaluated on the basis of carbon budget, its effectiveness to control fuel buildup, risks of starting catastrophic fires, or compromised air quality. Our book provides a comprehensive reference for researchers and land and air resources managers dealing with these complex issues of the interactions of wildland fire and air pollution.

Information presented in this book has been divided into four sections: I, General information and emissions; II, Ambient air quality, visibility, and human health—regional perspectives; III, Ecological impacts of forest fires and air pollution; and IV, Advances in remote sensing (RS), modeling, and management. This chapter provides an integrative synthesis of the book and presents the most important needs and recommendations for researchers and managers.

26.2. Integration of processes: causes and effects of wildland fires

26.2.1. Causes of wildland fires

Wildland fires are complex combustion processes involving various types of fuels and fire behaviors changing over time and space (Goldammer et al., this volume). Availability of fuel and fuel properties (Ottmar et al., this volume), as well as climatic and weather conditions, have a profound influence on wildland fire ignition potential, fire behavior, and fire severity (Benson et al., this volume). Air pollution, specifically elevated concentrations of ambient ozone (O_3) and nitrogen (N) deposition resulting from N pollutant emissions, predispose forests to adverse effects from drought, attacks of bark beetles, or other pests and diseases (Fig. 26.1). Indeed, impacts of air pollution may be increased with adverse climate change, escalating forest threat. Air-pollution-affected forests are characterized by increased presence of weakened or dead trees and a thick litter layer (easily available and highly combustible fuel) making them highly susceptible to catastrophic fires (Fenn et al., 1998; Grulke et al., this volume; Takemoto et al., 2001). Forest management and fire prevention management practices (Arbaugh et al., this volume), especially long-term prevention of all forest fires (such as that practiced for almost a century in the United States), have pronounced effects on probability of fire occurrence and fire severity (Minnich & Franco-Vizcaino, this volume). All of these complex processes can become more severe due to global warming (McKenzie et al., this volume) and a high incidence of arson

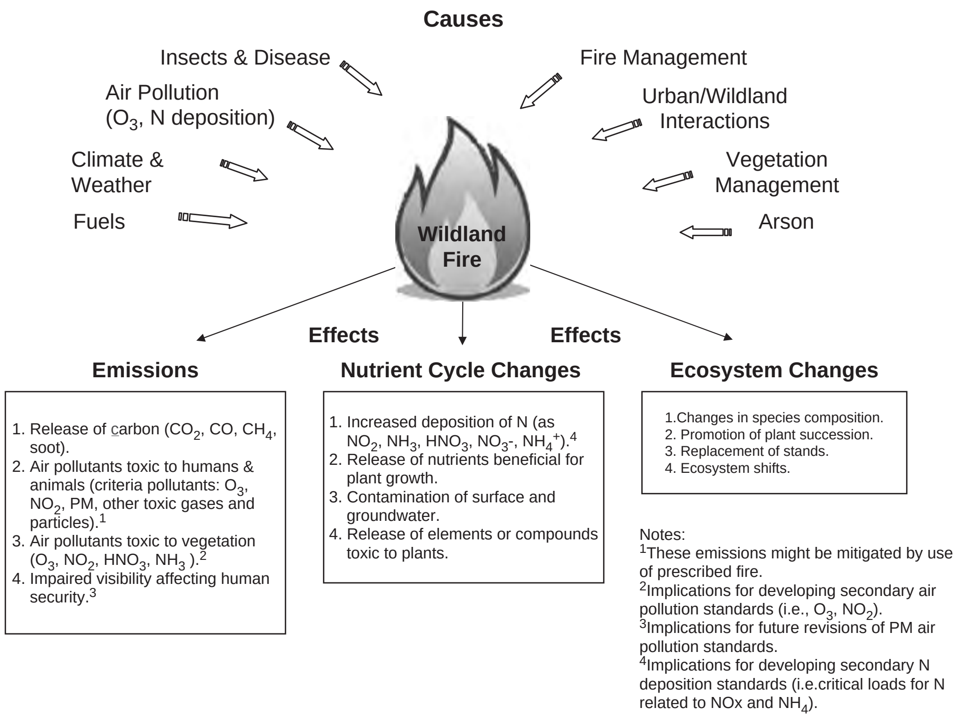

Figure 26.1. Integration of knowledge presented in Section I "General information and emissions" and Section III "Ecological impacts of forest fires and air pollution."

(Goldammer et al., this volume). Finally, large uncontrollable fires can result from climate pulses over large regions that have resulted in fire danger beyond any previously recorded level (Chubarova et al., this volume).

26.2.2. Effects of wildland fires

26.2.2.1. Emissions

Understanding potential fire emissions requires knowledge of fire sources that include size of the area burned, burn period, characteristics and condition of the fuels, amount of fuel consumed, and emission factors for specific pollutants (Ottmar et al., this volume). Smoke from fire is composed of hundreds of chemicals in gaseous, liquid, and solid forms that undergo complex chemical reactions and transformations. As a result, substantial concentrations of elemental carbon, volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), O_3, and particulate matter (PM) may be found downwind of fires, sometimes thousand miles from the source (Goldammer et al., this volume; Urbanski et al., this volume). Some of these compounds are classified as criteria pollutants (pollutants with established air quality standards), and these include NO_x, O_3, and PM, which affect human health, reduce visibility, and impact human security (Fig. 26.1; Goldammer et al., this volume). Numerous field studies and modeling efforts indicate that changing climate is likely to increase the extent and frequency of wildfires, highlighting the importance of accurately quantifying the regional and global effects of wildfire on carbon stocks and release of atmospheric carbon compounds (Conard & Solomon, this volume).

Visibility impairment is caused mostly by aerosols (both solid and liquid), and wildland fire smoke is one of the major sources of those at the global scale. Between 25% and 60% of the organic carbon (OC) measured in ambient air is a result of smoke from wildfire. In relation to estimated natural background values, this suggests that the vast majority of the natural background of OC aerosol in the western United States results from fire, while in the eastern United States nearly 50% of it may be due to fire. A significant portion of the remaining OC in the eastern United States is likely attributable to secondary aerosol formation from vegetation emissions of reactive hydrocarbons. Visibility in the United States is also affected by fine particles transported long distances from Asia and Africa (Fox & Riebau, this volume).

26.2.2.2. Changes in Nutrient Cycling

There is a distinctive difference between the effects of wildland and prescribed fires on N status of forests. Wildfire removes substantial quantities of N by volatilization, and prescribed fire, over time, can remove as much or more N than wildfire. However, this lost N can be quickly replaced if fire is followed by N_2-fixing vegetation. Wildfire often has short-term deleterious effects on water quality because of increased N mobilization, and long-term fire suppression allows buildup of N-rich litter, a source of labile N to runoff waters (Fig. 26.1). Prescribed fire usually has less impact on water quality than wildfire (Johnson et al., this volume).

In southern California, forest fire suppression and increased N deposition contribute to increasing fuel loads and to an alteration of N fuel content. Model simulations suggest that this will affect wildfire severity and result in increases in air pollution emissions from fires, increased soil N emissions right after fire, and elevated N export to stream water (Gimeno et al., this volume).

26.2.2.3. Changes in Ecosystems

Emissions from wildland fires may result in elevated concentrations of ambient O_3 and N pollutants (Goldammer et al., this volume; Urbanski et al., this volume). Grulke et al. (this volume) found that changes in forests impacted by air pollution may be creating increased fire hazards in forests near urban areas, which have already been predisposed to occurrences of high severity (catastrophic) fires by effective fire suppression used as the prevailing management strategy in the United States in the 20th century (USDA Forest Service, 2001). Catastrophic forest fires in southern California in 2003 clearly demonstrated the consequences of such changes due to air pollution (Keeley et al., 2004). These fires can cause long-term changes in species composition during various successional stages, or can even lead to a complete replacement of forests by other ecosystems, such as chaparral or steppe (Fig. 26.1; Minnich & Franco-Vizcaino, this volume). Grulke (this volume) provides a comprehensive synthesis of the effects of altered nutrient cycling and ecosystem processes caused by wildfires, air pollution, and changing climate.

26.3. Regional issues related to fires and emissions

Effects of forest fire emissions on air pollution in Europe are described in three complimentary chapters in this book that focus on the entire

European Union (Barbosa et al., this volume), southern Europe (Miranda et al., this volume), and central and eastern Europe (Szczygiel et al., this volume). About two-thirds of the fires occurred in southern Europe (France, Greece, Italy, Portugal, and Spain) where about half million hectares of forest land burn every year, representing around 86% of the total burned area in the European Union (Barbosa et al., this volume). In southern Europe, forest fires emit large quantities of pollutants every summer that result in severe air pollution episodes. These are caused mostly by emissions from forest fires but also by emissions from aircrafts used to fight the fires (Miranda et al., this volume). In central and eastern Europe, diversified and relative young forest stands and humid climate result in much lower (moderate) fire risk than in southern Europe. In that part of Europe between 1991 and 2001 about 387,680 fires burned 757,000 ha, which is just slightly more than the average area of forest burnt in southern Europe annually (Szczygiel et al., this volume).

Examples of the effects of wildland fire emissions on human health and safety are described in this book for two well-known recent events in Russia and in Ukraine. In summer 2002, the prolonged period of high temperatures and drought in central Russia resulted in large, long-lasting fires of peat bogs and forest that caused massive smoke emissions. Smoke was transported into Moscow for a period of almost 2 months, severely reducing visibility and exposing people to the unhealthy levels of air pollutants. The fire smoke cloud was characterized by high aerosol optical thickness and high concentrations of the optically active gas species such as elevated levels of O_3 (Chubarova et al., this volume). The Chernobyl nuclear power plant explosion in Ukraine in 1986 was one of the worst environmental disasters of recent times. The fallout and accumulation of radionuclides in the soil and vegetation have had long-term impacts on the surrounding area. It is feared that radionuclides released during potentially large, catastrophic vegetation fires (especially from the Chernobyl Exclusion Zone) could spread to continental Europe, Scandinavia, and Russia. The potential for large fire occurrence was assessed based on composition of radionuclides in soil, vegetation, and in PM emitted by fires. The highest atmospheric radionuclide ^{137}Cs levels occurred in early spring and late fall, corresponding to the most intense periods of burning in the Exclusion Zone. Satellite images showed that a smoke plume from the Exclusion Zone in May 2003 dispersed several hundred kilometers southeast, reaching the major metropolitan area of Kiev (Hao et al., this volume).

These incidents, along with the late 1990s and early 2000s exposures of southeast Asian and Indonesian populations to wildland and agricultural fire emissions (Goldammer et al., this volume), are some of the best known examples of the recent effects of wildland fire smoke on human populations. Similar events are expected to happen even more frequently, given the effects of changing climate (higher temperatures and increased drought) interacting with other stresses, such as the phytotoxic effects of air pollution. The probability of the occurrence of these events is very high in Asia, especially in rapidly developing China (Qu et al., this volume). In Australia wildland fires (bushfires) range from the annual savanna fires in the north to the sporadic but extensive forest fires in the south. In addition, prescribed burning is frequently being used as a means of reducing fuel loads, for maintenance of plant and animal biodiversity, and in forestry management practices. However, here little is known about production or composition of smoke from biomass burning and the effects of fire emissions on the human population. It has been recognized that emissions from bushfires or fuel-reduction burns need to be monitored and assessed. A large proportion of the vegetation of Australia is composed of forests dominated by native species of *Eucalyptus* and *Acacia*, while large expanses of plantations are dominated by single species of *Eucalyptus,* which are well-known emitters of VOCs. Consequently, Australia's environment is unique in terms of fuel type and emissions produced from these fuels in the generally low background levels of ambient air pollutants and very different fire regimes and fuel types in most of the country (Bell & Adams, this volume).

26.4. Remote sensing, modeling, and management issues

26.4.1. Remote sensing

Application of RS (both satellites and aircraft platforms) helps with monitoring fire occurrence, fire physical characteristics, and emissions (smoke) intensity and transport patterns (Goldammer et al., this volume). Among various systems used, the FireMapper system (Riggan & Tissell, this volume) provides new abilities to study wildlfire behavior and helps to incorporate improved fire intelligence in daily firefighting operations. The remotely acquired fire-behavior data sets form an important base that can be used for validating and improving fire-behavior simulation models.

In recent years China has begun using RS as a tool for monitoring regional fire hazards, and to a lesser extent, air quality emissions. Satellite instruments such as the Advanced Very High-Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer

(MODIS) have been used in Chinese field experiments and in routine monitoring of wildfires and air quality. In addition, the Landsat measurements have been used for land cover mapping to determine fuel type and loading to estimate fire emissions. All of these measurements can be useful for forest management and air quality management in China, given that forest fires could significantly increase under a warming global climate (Qu et al., this volume).

Hao et al. (this volume) recommend that a satellite receiving station to detect fires in real-time in the Chernobyl area, Ukraine, be installed. In addition, smoke dispersion and air quality forecasting model to predict the radioactivity levels downwind from catastrophic fires should be developed to reduce the risk of catastrophic exposures of inhabitants of the neighboring rural and metropolitan areas.

26.4.2. Models

Fire managers around the world use a variety of systems to track and predict fire danger and fire behavior at spatial scales that span from the local-to-global levels and at temporal scales ranging from minutes to seasons. Fire management software applications that usually incorporate one or more computer models can determine the types of planning tools used. Advanced computing technology has spawned a new generation of fire planning tools to predict fire occurrence and fire behavior. Linkages between different fire danger and behavior modeling systems and air quality models could greatly improve mapping and prediction of air pollution due to wildland fires (Fujioka et al., this volume).

Several real-time smoke prediction systems have been developed worldwide to help land managers, farmers, and air quality regulators balance land management needs against smoke impacts. Four systems that are currently operational for regional domains in North America and Australia link fire activity data, fuels information, and consumption and emissions models with weather forecasts and dispersion models to produce a prediction of smoke concentrations from prescribed fires, wildfires, or agricultural fires across a region. These real-time smoke prediction systems are providing a point of interagency understanding between land managers and air regulators from which negotiations of the conflicting needs of ecological fire use while minimizing air quality health impacts can start (O'Neill et al., this volume; Wain et al., this volume).

Various process-based models have been developed for forecasting PM and O_3 levels in the presence and absence of fires. Although these models provide deterministic predictions, few of them give measures of uncertainties associated with these predictions, which are essential for model evaluation and forecasting with known precision levels. A statistical procedure for accurate forecasting of next-day ozone levels by applying it to a real data set of the observed ambient ozone and weather values has been developed. Forecasted $PM_{2.5}$ values from the BlueSky Smoke Dispersion Model were tested as a proxy for the amount of O_3 precursors reaching a given site from specific fires. The forecasts from the statistical model may be useful as a tool for air quality managers to time-prescribed fire treatments (Preisler et al., this volume).

26.4.3. Management

The interaction between smoke and air pollution creates a basic conflict between public health and fuels treatments. Fuels treatments (prescribed fire and mechanical removal) proposed for forest and other wildlands are intended to reduce fuel accumulations and wildfire frequency and severity, as well as to protect property located in the wildland–urban interface (USDA Forest Service, 2001). However, prescribed fires produce toxic gases and aerosols that have instantaneous and long-term effects on air quality (Fang et al., 1999). If fuels treatments are not conducted, however, then wildfires may become more severe and frequent, resulting in elevated public health and safety effects. A better understanding of air pollution and smoke interactions is needed in order to protect the public health and allow for socially and ecologically acceptable use of fire as a management tool. This could be accomplished by innovative wide-scale monitoring efforts (field and remotely sensed) and development of models predicting spatial and temporal distribution of air pollution and smoke resulting from forest fires and other sources. These problems impact the general public, land managers, and policy makers, especially if urban areas or wildland-urban interfaces are affected. The U.S. Environmental Protection Agency (EPA) in cooperation with federal land managers, states, and tribes issued the Interim Air Quality Policy on Wildland and Prescribed Fire (EPA, 1998) to protect public health and welfare by mitigating the impacts of air pollutant emissions from wildland fires on air quality.

In California, fuels treatments on public lands are critical for reducing fuel accumulation and wildfire frequency and severity and for protecting private property located in the wildland–urban interface. Treatments are especially needed in forests impacted by air pollution and subject to climate change. Combinations of future climate variability and air pollution are likely to increase the risk of episodic tree mortality, long-term ecosystem changes, and increased frequency and severity of wildland fires. Fuel treatments, however, are difficult to implement in these forests.

Smoke from prescribed fires can adversely affect local and regional air quality, leading to conflicts with local and regional air-regulatory agencies. Federal air quality and fire managers have responded to these conflicting needs, actively forging cooperative relationships between fire managers and local, state, and federal air regulators. The result has been fewer conflicts about smoke in populated or protected areas while striving to achieve an adequate level of prescribed fire treatments. Social and regulatory acceptance of fire as a management tool in air-polluted forests will depend on land managers developing a better understanding of air pollution and smoke interactions and interactions between air pollution, drought, and insects. Acceptance of fire as a management tool also requires better large-scale monitoring efforts and development of models for predicting spatial and temporal distribution of air pollution and smoke from forest fires. Air pollution and climate effects have to be incorporated into forest mensuration models used to better predict forest stand development (Arbaugh et al., this volume).

Prescribed fire has also been proposed as a management tool to mitigate N saturation (a result of chronic, excessive N deposition). However, a major limitation of this strategy is that while fire removes substantial quantities of N from the forest floor, it removes only a small fraction of the large N reservoir in the mineral soil and at the same time causes increases in soil ammonium over the short term. Periodic prescribed fire to reduce fuel loads and atmospheric N deposition (through control of N air pollution) and strategies to enhance plant and microbial N demand may all be required to reduce N saturation symptoms in catchments exposed to long-term atmospheric N inputs (Gimeno et al., this volume; Johnson et al., this volume). Past and future vegetation and fire management activities also play a role in ecosystem potential to store carbon. The nature and magnitude of these impacts vary greatly among regions and ecosystems (Conard & Solomon, this volume).

To monitor and minimize the transboundary effects of air pollution resulting from vegetation fires, international policies based on science are needed to avoid excessive fire application and to establish effective fire and smoke management practices and protocols of cooperation at the international level (Goldammer et al., this volume).

26.5. Research and management needs and recommendations

This book has provided a wide range of research studies, monitoring tools, and management practices that focus on the interactions of fire and air pollution. Based on this knowledge and information, we present the following future research needs and recommendations.

26.5.1. Fuels

- More detailed characteristics of complex fuels are required for the development of more precise fire-behavior models. Specifically, improved knowledge of moisture content and its effects on ignition and combustion efficiency, spatial and qualitative complexity of fuels, vertical and horizontal description of fuel beds, and combustion characteristics of rotten fuel and organic layers are needed.
- Better methods for mapping real fuel characteristics at the broad scales relevant for regional air quality modeling, and for understanding how small-scale variation can be captured in broad-scale data are required.

26.5.2. Climate/weather

- Improved weather forecasting of changing climate/atmospheric circulations at the local-to-regional scales are recommended, as well as more precise seasonal forecasts to better predict fire behavior.
- Better understanding of atmosphere/biosphere interactions that may result from the increase of greenhouse gases in the atmosphere is needed.
- Full physics-based models of fire behavior that incorporate interactions with the atmosphere need to be developed.
- To improve fire danger and fire-behavior modeling, very fine scale (48- to 96-hour) wind simulations in complex terrain at the scale of tens of meters that are linked to mesoscale weather are needed.
- Because current resolution of regional climate models is too low ($\sim$50 km), more accurate empirical and statistical downscaling tools need to be developed for assessing the impact of climate change on fire behavior and fire emissions.

26.5.3. Fire detection

- Continued improvement in fire detection capabilities, especially in regard to size estimates and actual fuel consumed, are necessary. Specifically, high-resolution fire imagery is needed in real-time to monitor and map fire activity and smoke dispersion.
- Remote Sensing of fire occurrences should assess fire dynamics and be integrated with information on fire intensity (which can be derived

from the fire-radiative energy). This approach would help in a better assessment of fire effects and smoke emissions.

- Mapping burn scars and fire intensity using a variety of satellite data is needed for inventory of the effects of fires on forest and other ecosystems.

26.5.4. Prediction of fire behavior

- Better linkage of fire behavior models with atmospheric dispersion and air quality models is needed. Improved coupled fire-atmosphere models should help to predict the effects of fire on atmospheric processes.
- Physics-based models of fire behavior that function on small to large scales and include more accurate dynamics of fire behavior (such as extreme fire behaviors—both spot and crown fires) are needed. These models would provide levels of uncertainty that are essential for fire prediction in operational fire management (see Section 26.5.2).
- In-situ observations at the fire-atmosphere interface are recommended to validate fire behavior models.
- Improved forecasts for lightning events at the short and medium range are necessary.
- More sophisticated models are needed to understand the coupling between the atmosphere and vegetation under increased atmospheric carbon dioxide scenarios.

26.5.5. Emissions chemistry and in-plume chemistry

- Improved characterization of emissions of air pollutants and greenhouse gases during fire events is needed to increase accuracy of international emissions estimates. Consequently, more and better field studies on fuel consumption and emissions in various natural fuel beds should be conducted.
- Emissions from peat and bog fires, which are extremely important for greenhouse gas inventories and understanding extreme smoke events in the northern hemisphere, must be better understood and characterized.
- Treatment of fire emissions (including H_2O) in the models simulating atmospheric chemistry and formation of secondary aerosols should be improved.
- Chemical synthesis of forest fire smoke as the synergistic or the additive result of different types of fuels burnt and materials contained in the smoke haze must be investigated (especially when the forest fire front expands into the urban-rural interface).

- Field studies designed to measure smoke concentrations in three dimensions (not just at the surface) should be conducted. Use of an unmanned aerial vehicle (UAV) with $PM_{2.5}$ (and other trace gas species) monitors or canister samples for chemical analysis should be considered.
- Detailed identification and chemical analysis of functional groups of VOCs is needed to develop markers (gaseous or aerosol tracers) that could be used to distinguish smoke from prescribed versus wildland fires.
- To improve air quality models, the treatment of smoke plumes as they move and encounter pollutants from other sources need to be tested and improved. This is crucial for understanding secondary aerosol formation or ozone generation.
- Effects of chronic N deposition and N accumulation in ecosystem on fire emissions chemistry should be better understood.
- Measurements of plume heights, dynamics, movement, and aerosol properties are needed in order to validate smoke dispersion models.
- The unique fuel types and emissions in Australian environments (low levels of air pollution in much of the country in contrast to fire regimes and fuel types from north to south) could be used as a testing ground for future emission studies.

26.5.6. Ambient air quality

- Real-time monitoring of ambient air quality during forest fires, using improved field analytical methods is recommended to assess potential impacts to public health.
- Regional air quality models need to include realistic wildland fire emissions. Therefore, fire prediction models must be used in conjunction with smoke prediction models, especially to quantify the spatial and temporal dynamics of fire emissions.
- Fire behavior models should be coupled with meteorological and chemical models for improved pollution transport models. Transport patterns, spatial and temporal distributions of pollution plumes, and complexity of mountain terrain and effects of changing climate should be better characterized in such models, which could lead to improved accuracy and precision of predictions.
- Air quality forecasting models predicting pollutant levels downwind from large fires and catastrophic mega-fires should be developed. These models should be verified during large-scale field measurement campaigns.

- Long-range transport of pollutants (trans-Pacific, trans-Atlantic, and cross-continental) that may affect background levels of pollutants toxic to humans and vegetation should be evaluated.

26.5.7. Carbon release and greenhouse effects

- Information on the extent and severity of fire, the feedbacks between fire and climate, and the effects of changing fire regimes on all aspects of the carbon cycle is recommended before we can fully predict the magnitude, or perhaps even the direction, of the effect of changing fire regimes on global carbon balance, greenhouse gas emission, and atmospheric chemistry. To accomplish this, much better information about the amount of burned biomass, especially during wildfires, is needed, as well as a better understanding of industrial and urban sources of carbon release.
- Valid, accurate, and precise emissions inventories have to be developed and maintained by countries for all fire types, especially in those regions where fire is significant. This is especially true as the next generation of carbon accounting is developed.
- The relationship between changing fire and agricultural regimes should be better understood and included in the greenhouse gas mitigation strategies.

26.5.8. Ecological impacts on forests

- The effects of ozone and nitrogen atmospheric deposition must be better understood, as well as the interactions among various pollutants, drought, and pests on the composition, structure, and function of forests and other ecosystems. This research should include the effects of these pollutants on biodiversity, including changes in vegetation, wildlife, insects, soil invertebrates, and soil microorganisms.
- Critical loads of atmospheric deposition, thresholds of toxic effects of air pollutants, and sensitive receptors that can be easily identified must be determined for the protection of wilderness and ecosystem values from the effects of wildfire emissions and other types of air pollution exposures.
- Long-term effects of fire on nutrient budgets (especially carbon, nitrogen, and phosphorus), in forest ecosystems should be determined.
- Models aimed at better understanding of the effects of air pollution and climate change on forests at the landscape scale (that incorporate topography, land use, etc.) are needed.

26.5.9. Health effects of smoke

- The quantification of hazardous compounds in smoke from biomass burning should be used in risk analysis of health and safety of firefighters and the general public during wildfire and prescribed burning activities. This would allow for a better-informed decision-making process.
- Representative key indicators (target forest-fire smoke compounds) for monitoring of air quality during wildland firefighting operations should be defined.
- Effectiveness of personal protective equipment for firefighters and the exposed population should be tested.
- Long-term effects of smoke exposure on the health of firefighters should be understood. In order to accomplish this goal, some novel approaches (e.g., chemical analysis of expired air) should be used.
- Exposure limits to hazardous compounds during forest fire and evacuation criteria for sensitive groups of population should be determined.

26.5.10. Management issues

- Because smoke affects air quality and therefore must be measured so that air quality can be improved, a better link between forest fire and air quality communities is needed.
- Data generated by meteorological and smoke prediction systems should be meaningfully and usefully delivered to the user communities (land managers, air quality regulators). Continued collaboration is required between the tool developers and the users if benefits of scientific advancements are to be realized. Effective use of information management concepts should be applied to improve usefulness of data and to safeguard it.
- Effective collaboration between air resources and land managers is needed to evaluate opportunities to increase the utility of prescribed fire to treat accumulated fuels in wildlands. Increased air monitoring efforts and development of probabilistic dispersion models to better manage smoke and minimize public health impacts are recommended. The existing knowledge on the use of prescribed fire and its effects on air quality should be effectively implemented in future management plans.
- Effective technology development addressing new problems, challenges, and program elements is needed. It should include development of new technologies for fire and air quality monitoring, information

management, and modeling. Strong linkages between specialists in various fields (fire sciences, climatology, atmospheric sciences, forestry, ecology, and others) are recommended.

- Successful air resource management based on close coordination with other land managers, air resource specialists, researchers, air-regulatory agencies, and public and private organizations with environmental interests is strongly encouraged.
- Tradeoffs between short-term smoke management and the potential for greater future impacts from restricting prescribed fires and by suppressing fires must be better understood.
- Comparison of land management options used in the northern hemisphere (e.g., Europe, United States, and Canada) with those used in the southern hemisphere (e.g., Australia and New Zealand) is needed given the wide variability of wildfires and the effects of air pollution in these different environments and ecosystems.
- Effects of large fires and mega-fires on air quality and the implications for public health have to be better understood. Occurrence of such fires is increasing in both the northern and southern hemispheres, perhaps as a result of record-breaking fire weather extremes exacerbated by increased climate variability. Profound advances in fire and air quality science are needed for characterizing these fire classes and should be considered imperative.

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