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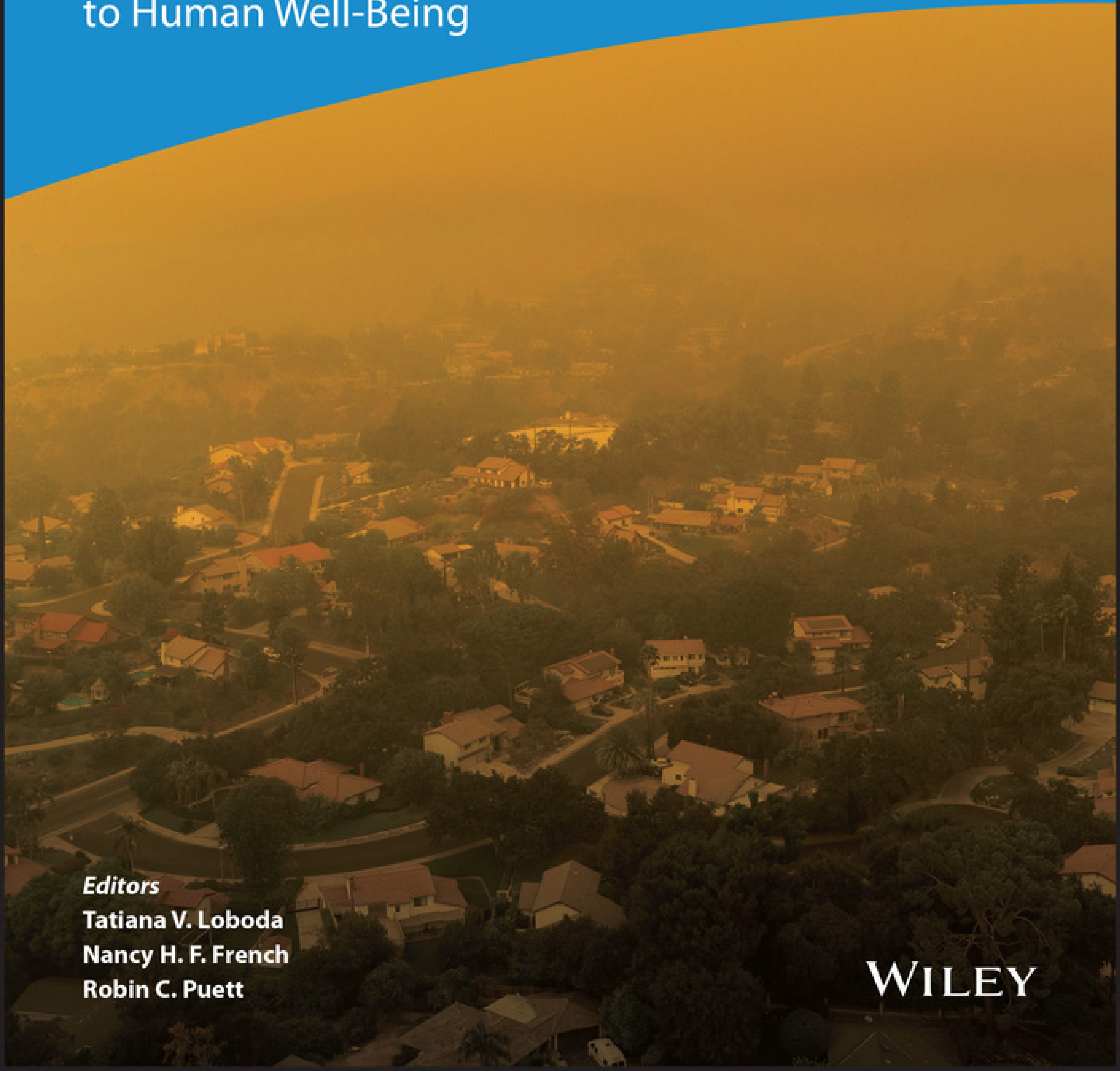
Landscape Fire, Smoke, and Health

Linking Biomass Burning Emissions to Human Well-Being



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280 **Landscape Fire, Smoke, and Health: Linking Biomass Burning Emissions to Human Well-Being** *Tatiana V. Loboda, Nancy H. F. French, and Robin C. Puett (Eds.)*

Geophysical Monograph 280

Landscape Fire, Smoke, and Health

Linking Biomass Burning Emissions to Human Well-Being

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PREFACE

Smoke from biomass burning is known to be a significant source of air pollution, and smoke inhalation is well understood to be detrimental to human health. Developing approaches to quantify the impacts of biomass burning smoke on health and well-being began with the need to protect wildland firefighters and the general public from smoke. In the United States, the Forest Service initially, and the Environmental Protection Agency and National Weather Service in more recent years, developed the science, measurements and analysis frameworks for responding to the threat of air pollution coming from landscape fires. Similar agencies in other developed regions of the world, such as Canada's FireWork system and the Emergency Management Services in the European Copernicus program, provide important information for dealing with biomass burning pollution. More recently, advanced approaches using satellite-derived information combined with in situ measurements and advanced data assimilation and analysis techniques have allowed for improved retrospective assessments of air pollution from biomass burning as well as predictions on where and when smoke can be expected to intersect with human populations.

The focus of this volume is on describing the observational and modeling approaches that are currently used in fire science, smoke characterization, and health assessment, some of which are operationally employed, while others are at the forefront of research. The concepts, analytical approaches, and models that have been developed in these disciplinary camps provide exceptional capability to answer questions and solve problems related to the topic of biomass burning smoke exposure and health. Their application now, however, is required across the broad transdisciplinary space in order to address a complex set of concerns. With the transdisciplinary reach of scientific inquiry and modeling efforts comes the necessity of building a foundational understanding of approaches, methods, and tools to craft seamless and robust chains of data analysis. This book is written by leading experts (researchers, modelers, practitioners) from several disparate disciplines who have worked across disciplines, providing synthesis of activities from an international perspective through inclusion of lead authors and coauthors from several countries outside of North America. Our diverse international and multidisciplinary community of authors and reviewers highlights the "common language" challenge faced when connecting across established divides. One clear focus of this book is on gaining an improved vocabulary and transdisciplinary knowledge-set for considering solutions. The authors have written the text to be comprehensible to experts in the other fields of the modeling chain, with the dual aims of making a subset of this book of value to all experts currently working in this domain, as well as making all components of this book of value to newcomers to the field. Scientific discovery and technological development often outpace scientific publishing and, thus, books focused exclusively on cutting edge knowledge tend to become outdated before they come out of print. For this book, we include information that will provide the scaffolding for accelerated scientific growth.

The book is simplistically structured to cover a broad set of related topics, presented to be accessible outside of an expert's basic knowledge field, and provides foundational concepts along with new research and applications. The book is divided into three parts, which broadly address fire science (Part I: From Fires to Emissions), atmospheric chemistry and dynamics (Part II: From Emissions to Concentrations), and human health research (Part III: From Concentrations to Health Outcomes). Each part contains four chapters, which are designed to cover the foundational knowledge within the field; highlight recent advancements; describe commonly used methods; and outline existing data sets, models, or systems in general use by the respective communities. The three parts of this volume represent three distinct research communities, with members who are often focused on topics adjacent to the topics of fire, smoke, and health. Included are in-depth reviews of the state of the art within each topic aimed at understanding health outcomes of biomass burning emissions (smoke).

Since the AGU's Fall Meeting in 2019 when we first convened a session related to health outcomes of biomass burning emissions, we have evidenced the widespread attention and the rapidly growing interest in this subject among the scientists, resource managers, and public health practitioners. However, it also became clear that the community was largely involved in advancing the science within its disciplinary camps with limited communication and collaboration among scientists involved across various components of the modeling chain (starting with fire detection, through emissions modeling, atmospheric transport, and constructing epidemiological models of health outcomes). As a result, researchers along the modeling chain have struggled to identify and incorporate the most appropriate developments from adjacent disciplinary links into developing their methodologies. Moreover, the rapid proliferation of methods for each of these components has also created challenges evaluating the validity and linkages among reported results leading to opaque science. In this book, we attempt to synthesize and harmonize foundational as well as state-of-the-art information across all components of the modeling chain and to build a common language to advance transdisciplinary work. While far from comprehensive, the primary aim of this book is to build a collaborative community with a common understanding and to promote further scientific inquiry and applied approaches.

A book like this, with a diverse set of authors and broad audience, takes dedication and patience from the people involved. We would first like to acknowledge the effort that each of our chapter lead authors and coauthors put into writing excellent and valuable material that makes up the bulk of this volume. In addition to thanking these dedicated authors, we thank Jenny Lunn at AGU, Geeta Persad from the AGU Books Editorial Board, and the production team at Wiley including Keerthana Govindarajan, Noel McGlinchey, Rituparna Bose, and Lesley Fenske. They have been quite gracious in guiding us along the path to completion. Also, in the background making sure materials flowed efficiently was Julie Carter, who read each chapter draft for consistency, a task of great value and payoff for making a good product. In addition, the quality of the work is due in large part to the set of reviewers who graciously provided their time and expertise to critiquing each chapter. A full-fledged peer review takes time and effort on the part of many people. Finally, a thank you to the AGU Geohealth Section leaders, session organizers over the past three years, and section members for encouraging us to take on this project. The AGU embraces the philosophy of diversity of thought and development of transdisciplinary bridges. The Geohealth Section, in particular, has shown the way to improving health and well-being with this approach.

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ACRONYMS AND ABBREVIATIONS

Acronym	Description	Chapter
AATSR	Advanced Along-Track Scanning Radiometer	3
ABI	Advanced Baseline Imager	3
ACCESS	Australian Community Climate and Earth-System Simulator	9
ACCP	Aerosol and Cloud Convection and Precipitation	2
ADME	Absorption, Distribution, Metabolism, and Excretion	11
ADRD	Alzheimer's Disease Related Dementias	12
AERONET	Aerosol Robotic Network	7
AFAC	Australian National Council for Fire and Emergency Services	2
AFDRS	Australian Fire Danger Rating System	9
AFIS	Advanced Fire Information System	2
AHI	Advanced Himawari Imager	3
AhR	Aryl Hydrocarbon Receptor	11
AIRPACT	Air Indicator Report for Public Awareness and Community Tracking	8
ALS	Airborne Light detection and range Scanning	4
AMS	Autonomous Modular Sensor	3
AOD	Aerosol Optical Depth	6
AOS	Atmosphere Observing System	2
API	Application Programming Interface	6
AQ	Air Quality	6
AQFx	Air Quality Forecasting	9
AQHI	Air Quality Health Index	9
AQI	Air Quality Index	11
ARI	Acute Respiratory Illness	11
ASEAN	Association of Southeast Asian Nations	9
ASMC	ASEAN Specialized Meteorological Centre	9
ATS	American Thoracic Society	10
ATSR-2	Along-Track Scanning Radiometer 2	3
AVHRR	Advanced Very High Resolution Radiometer	3
BAER	Burned Area Emergency Response	2
BB	Biomass Burning	9
BC	Black Carbon	9
BEIS	Biogenic Emission Inventory System	9
BLANkET	Base-Line Air Network of EPA Tasmania	9

BMI	Body Mass Index	13
BOM	Bureau of Meteorology (Australia)	9
BSC	BlueSky Canada	9
BSC-S	Barcelona Supercomputing Center (Spain)	9
CAAQMS	Continuous Ambient Air Quality Monitoring Stations	6
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization	7
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations	2
CAMS	Copernicus Atmosphere Monitoring Service	9
CANSAC	California and Nevada Smoke and Air Committee	9
CAP	Criteria Air Pollutants	5
CASTNet	Clean Air Status and Trends Network	6
CAWFE	Coupled Atmosphere-Wildland Fire Environment	2
CCI	Climate Change Initiative	3
CDF	Cumulative Distribution Function	7
CEOS	Committee on Earth Observation Satellites	2
CFD	Computational Fluid Dynamics	4
CFFEPS	Canadian Forest Fire Emissions Prediction System	9
CH4	Methane	5
CI	Confidence Interval	13
CMAQ	Community Multiscale Air Quality	10
CNEMC	China National Environmental Monitoring Center	6
CNES	Centre National d'Etudes Spatiales (France)	2
CO	Carbon Monoxide	5
CO2	Carbon Dioxide	5
COHb	Carboxyhemoglobin	11
CONAFOR	Comisión Nacional Forestal (Mexico)	2
CONUS	Continental United States	7
COPD	Chronic Obstructive Pulmonary Disease	10
CRF	Concentration-Response Functions	12
CrIS	Cross-Track Infrared Spectrometer	7
CSA	Canadian Space Agency	2
C-SEM	CSIRO Smoke Emissions Model	9
CSIRO	Commonwealth Science and Industrial Organization (Australia)	9
CSMS	Coordinated Smoke Management System	9
CTM	Chemical Transport Model	10
CWD	Coarse Woody Debris	4
CWFIS	Canadian Wildland Fire Information System	2
DEASCO3	Deterministic and Empirical Assessment of Smoke's Contribution to Ozone Project	9
DEHM	Danish Eulerian Hemispheric Model	9

DELWP	Department of Environment, Land, Water, and Planning (Victoria, Australia)	9
DEP	Diesel Exhaust Particulate	11
DMSP	Defense Meteorological Satellite Program	3
DOI	Department of the Interior (United States)	2
DPIE	Department of Planning, Industry, and the Environment (New South Wales, Australia)	9
DRI	Desert Research Institute	9
DTM	Digital Terrain Models	5
ECCC	Environment and Climate Change Canada	9
ECMWF	European Centre for Medium-Range Weather Forecasts	9
EEA	European Environment Agency	5
EF	Emission Factor	5
EFFIS	European Forest Fire Information System	2
EJScreen	Environmental Justice Screening	2
EMEP	European Monitoring and Evaluation Programme	5
ENEA	Energia Nucleare ed Energie Alternative (Italy)	9
ENVISAT	Environmental Satellite	3
EOS	Earth Observing System	3
EOSDIS	Earth Observing System Data and Information System	2
EPA	Environmental Protection Agency	2
ERS-2	European Remote Sensing 2	3
ETM	Enhanced Thematic Mapper	3
EU	European Union	5
EURAD-IM	EURopean Air pollution Dispersion-Inverse Model	9
EVT	Existing Vegetation Type	5
EWS	Early Warning Systems	12
FASMEE	Fire and Smoke Model Evaluation Experiment	2
FBP	Fire Behavior Prediction	9
FCCS	Fuel Characteristic Classification System	5
FEER	Fire Energetics and Emissions Research	5
FEMA	Federal Emergency Management Agency (United States)	2
FEPS	Fire Emission Production Simulator	10
FFDI	Forest Fire Danger Index	9
FINN	Fire INventory from NCAR	8
FireMARS	Fire Monitoring Accounting and Reporting System	2
FIREX-AQ	Fire Influence on Regional to Global Environments and Air Quality	2
FIRMS	Fire Information for Resource Management System	2
FIS	Fire Information System	9
FLAMBE	Fire Locating and Modeling of Burning Emissions	9
FLEXPART	Flexible Particle dispersion model	8

FMI	Finnish Meteorological Institute	9
FNMOC	Fleet Numerical Meteorology and Oceanography Center	9
FOFEM	First Order Fire Effects Model	5
FPA	Forest Practices Authority (Tasmania, Australia)	9
FRE	Fire Radiative Energy	3
FRM	Federal Reference Method	10
FRP	Fire Radiative Power	3
FT	Free Troposphere	8
FWI	Fire Weather Index	9
GA	Gaussian Anamorphosis	7
GAFIS	Global Air Quality Forecasting and Information System	9
GAM	Generalized Additive Model	6
GBA	Global Burnt Area	3
GBBEP-Geo	Global Biomass Burning Emission Product from Geostationary Satellites	5
GBBEPx	blended Global Biomass Burning Emissions Product	9
GDPFS	Global Data-Processing and Forecasting System	9
GEDI	Global Ecosystem Dynamics Investigation	5
GEFS	Global Ensemble Forecast System	9
GEM	Global Environmental Model	9
GEMS	Geostationary Environmental Monitoring Spectrometer	2
GEOS	Goddard Earth Observing System	9
GEOS-Chem	Goddard Earth Observing System with Chemistry	2
GFAS	Global Fire Assimilation System	5
GFED	Global Fire Emissions Database	5
GFMC	Global Fire Monitoring Center	2
GFS	Global Forecast System	8
GFWED	Global Fire Weather Database	2
GHG	Greenhouse Gases	5
GMS	Geostationary Meteorological Satellites	2
GOES	Geostationary Operational Environmental Satellite	2
GOFC-GOLD	Global Observation of Forest Cover - Global Observation of Land Dynamics	2
GPS	Global Positioning Systems	10
GSL	NOAA Global Systems Laboratory (United States)	9
GTOS	Global Terrestrial Observing System	2
GWIS	Global Wildfire Information System	2
GWR	Geographically Weighted Regression	6
HAPs	Hazardous Air Pollutants	12
HAQAST	Health and Air Quality Applied Sciences Team	2
HMS	Hazard Mapping System	2

HONO	Nitrous Acid	8
HRRR	High Resolution Rapid Refresh	9
HRRR-Smoke	High Resolution Rapid Refresh Model with Smoke	8
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory Model	8
IASI	Infrared Atmospheric Sounding Interferometer	7
IAWF	International Association of Wildland Fire	2
ICAP-MME	International Cooperative for Aerosol Prediction Multi-Model-Ensemble	9
ICESat-2	Ice Cloud And Land Elevation Satellite	5
IDEQ	Idaho Department of Environmental Quality (United States)	9
IDW	Inverse Distance Weighting	6
IEK	Institute of Energy and Climate Research (Germany)	9
IEP-NRI	Institute of Environmental Protection – National Research Institute (Poland)	9
IMPROVE	Interagency Monitoring of Protected Visual Environment (United States)	6
INERIS	Institut National de l'Environnement Industriel et des Risques (France)	9
INPE	Instituto Nacional de Pesquisas Espaciais (Brazil)	2
IPCC	Intergovernmental Panel on Climate Change	5
IS4FIRES	Integrated Monitoring and Modeling System (IS) for wildland fires	9
ISA	Integrated Science Assessment	10
ISRO	Indian Space Research Organization	2
IWFAQRP	Interagency Wildland Fire Air Quality Response Program	9
JAXA	Japan Aerospace Exploration Agency	2
JFSP	Joint Fire Science Program (United States)	2
JMA	Japan Meteorological Agency	3
JPSS	Joint Polar Satellite System	2
KNMI	Royal Netherlands Meteorological Institute	9
LANCE	Land, Atmosphere Near-real-time Capability for EOS	3
LAR	Laboratory for Atmospheric Research	9
LCAQS	Low-Cost Air Quality Sensors	6
LPDMs	Lagrangian Particle Dispersion Models	8
LRTAP	Long-Range Transboundary Air Pollution	5
LUR	Land Use Regression	6
LWIR	Long Wavelength Infrared	3
MAIA	Multi-Angle Imager for Aerosols	2
MAIAC	Multi-Angle Implementation of Atmospheric Correction	7
MASINGAR	Model of Aerosol Species in the Global Atmosphere	9
MCE	Modified Combustion Efficiency	5
MEGAN	Model of Emissions of Gases and Aerosols from Nature	9
MERIS	Medium Resolution Imaging Spectrometer	3
MFLEI	Missoula Fire Laboratory Emission Inventory	8

MINNI	Italian National Integrated Assessment Model	9
MISR	Multiangle Imaging SpectroRadiometer	2
MODIS	Moderate Resolution Imaging Spectroradiometer	3
MONARCH	Multiscale Online Nonhydrostatic AtmospheRe CHemistry model	9
MONCAGE	Météo France Modèle de Chimie Atmospherique à Grande Echelle	9
MOPITT	Measurement of Pollution in the Troposphere	7
MOVES	EPA MOtor Vehicle Emission Simulator (United States)	9
MOZART	Model of Ozone and Related Chemical Tracers	8
MPLNet	Micropulse Lidar Network	7
MSC	Meteorological Service of Canada	9
MSI	MultiSpectral Instrument	3
MSS	Multispectral Scanner System	3
MSS-S	Meteorological Service Singapore	9
MSS-UKMO NAME	MSS-United Kingdom Meteorological Office Numerical Atmospheric-dispersion Modeling Environment	9
MWIR	Medium Wavelength InfraRed	3
NAAPS	Navy Aerosol Analysis and Prediction System (United States)	7
NAAQMN	National Ambient Air Quality Monitoring Network (United States)	6
NAAQS	National Ambient Air Quality Standards (United States)	10
NAM	North American Mesoscale Forecast System	8
NAPS	National Air Pollution Surveillance (Canada)	6
NAQFC	National Air Quality Forecast Capability (United States)	9
NASA	National Aeronautics and Space Administration (United States)	2
NCAP	National Clean Air Program (India)	6
NCAR	National Center for Atmospheric Research	8
NEI	National Emissions Inventory (United States)	5
NEPMs	National Environment Protection Measures (Australia)	6
NESDIS	National Environmental Satellite, Data, and Information Service (United States)	12
NFPA	National Fire Protection Association	2
NH_3	Ammonia	5
NICC	National Interagency Coordination Center (United States)	2
NIFC	National Interagency Fire Center (United States)	2
NIROPS	National Infrared Operations (United States)	3
NISAR	NASA-ISRO Synthetic Aperture Radar	2
NO	Nitrogen Monoxide	5
NO_2	Nitrogen Dioxide	5
NOAA	National Oceanic and Atmospheric Administration (United States)	2
NOx	Nitrogen Oxides	10
NRC	National Research Council (United States)	10
NRCan	National Resources Canada	9

NRL	Naval Research Laboratory (United States)	9
NW-AIRQUEST	Northwest International Air Quality Environmental Science and Technology	9
NWCG	National Wildfire Coordination Group (United States)	2
NWP	Numerical Weather Prediction	9
NWS	National Weather Service (United States)	2
O_2	Molecular Oxygen	8
O_3	Ozone	5
OC	Organic Carbon	9
OLCI	Ocean and Land Color Instrument	3
OLI	Operational Land Imager	3
OLS	Operational Linescan System	3
OM	Organic Matter	9
OMI	Ozone Monitoring Instrument	7
OMPS	Ozone Mapping Profiler Suite	7
OR	Odds Ratio	13
PAHs	Polycyclic Aromatic Hydrocarbons	11
PBL	Planetary Boundary Layer	8
PDF	Probability Distribution Function	7
PM	Particulate Matter	5
PM_{10}	Particulate Matter with a diameter of 10 μ m or less	7
$PM_{2.5}$	Particulate Matter with a diameter of 2.5 μ m or less	7
PMAp	Polar Multisensor Aerosol product	9
POLDER	Polarization and Directionality of the Earth's Reflectances	7
PPE	Personal Protective Equipment	10
PRH	Pseudo Relative Humidity	7
PTSD	Post-Traumatic Stress Disorder	10
pyroCb	Pyrocumulonimbus	8
pyroCu	Pyrocumulus	8
QFED	Quick Fire Emissions Data set	9
RAP	Rapid Refresh	9
RAQDPS-FW	Regional Air Quality Deterministic Prediction System with near-real-time wild Fire Emissions	9
RF	Random Forest	6
RR	Relative Risk	13
RSMC	Regional Specialized Meteorological Centers (WMO)	9
SAR	Synthetic Aperture Radar	3
SASEM	Simple Approach Smoke Estimation Model	8
SBG	Surface Biology and Geology	2
SDS-WAS	Sand and Dust Storm Warning Advisory and Assessment System	9

SERA	Smoke Emissions Repository Application	5
SEVIRI	Spinning Enhanced Visible and Infrared Imager	3
SfM	Structure-from-Motion	4
SILAM	System for Integrated modeling of Atmospheric coMposition	9
SLSTR	Sea and Land Surface Temperature Radiometer	3
SMARTFIRE v2 (SF2)	Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation	9
SMHI	Swedish Meteorological and Hydrological Institute	9
SMOKE	Sparse Matrix Operator Kernal Emissions	8
S-NPP	Suomi National Polar-orbiting Partnership (United States)	3
SO2	Sulfur Dioxide	5
SOA	Secondary Organic Aerosols	8
SPOT	Satellite Pour l'Observation de la Terre	3
STILT	Stochastic Time-Inverted Lagrangian Transport	8
SWIR	Short Wavelength InfraRed	3
TEMPO	Tropospheric Emissions: Monitoring of Pollution	2
3D	Three Dimensional	4
TIROS-N	Television Infrared Observation Satellite - Next generation	3
TLS	Terrestrial Light detection and range Scanning	4
TM	Thematic Mapper	3
TNO	The Netherlands Organization for applied scientific research	9
TPM	Total Particulate Matter	5
TRAP	Traffic-Related Air Pollution	11
TRMM	Tropical Rainfall Measuring Mission	3
TROPOMI	Tropospheric Monitoring Instrument	7
TRP	Transient Receptor Potential	11
TSP	Total Suspended Particles	5
UAS	Uncrewed Airborne Systems	3
UKMO	UK Met Office	9
UNECE	United Nations Economic Commission For Europe	5
UNFCCC	United Nations Framework Convention On Climate Change	5
USDA	United States Department of Agriculture	9
USFS	United States Forest Service	8
USGS	United States Geological Survey	2
VACES	Versatile Aerosol Concentration Enrichment System	11
VAQUM	Verification of Air QUality Models (ECCC)	9
VAS	Visible Infrared Spin Scan Radiometer	3
VFSP-WAC	Regional VFSP-WAS Centers	9
VFSP-WAS	Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System	9
VIIRS	Visible Infrared Imaging Radiometer Suite	3

VIRS	Visible and Infrared Scanner	3
VOC	Volatile Organic Compounds	9
WACCM	Whole Atmosphere Community Climate Model	9
WFAS	Wildland Fire Assessment System	2
WFDS	Wildland-urban interface Fire Dynamics Simulator	8
WFEI	Wildland Fire Emissions Inventory	5
WFEIS	Wildland Fire Emissions Inventory System	5
WFRT	Weather Forecast Research Team	9
WHO	World Health Organization	2
WIMS	Weather Information Management System	10
WMO	World Meteorological Organization	9
WRAP	Western Regional Air Partnership (United States)	9
WRF	Weather Research and Forecasting model	2
WRF-Chem	Weather Research and Forecasting model with Chemistry	8
WRF-SFIRE	Weather Research and Forecasting model with Sfire Fire Spread Model	8

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Bridging Geophysical and Health Sciences to Study the Impacts of Biomass Burning on Human Well-Being

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ABSTRACT

Biomass burning in natural and management fires is a known source of air pollution that impacts millions of people worldwide. However, quantifying this impact and establishing definitive linkages between fire smoke and adverse health effects is a highly complex problem, which requires collaborative work between researchers across numerous disciplines within geophysical and health sciences. This chapter introduces the framework for this book and how we lay out the components of modeling chain from fire through smoke transport to health outcomes. Most of the concepts and models used in this modeling chain have been developed within disciplinary camps but are applied within a broad transdisciplinary research space. Our primary goal for this monograph is to build the foundation of common understanding of the entire process for nonspecialists in the field. And to achieve that, we aim to create a shared language, which interdisciplinary, transdisciplinary, and multidisciplinary teams of investigators might use to make their research efforts more robust and accelerate the pace of new knowledge development.

1.1. INTRODUCTION

Fire has been a part of the Earth system for at least 420 million years (Glasspool et al., 2004). Ever since levels of atmospheric oxygen produced by terrestrial vegetation rose enough to sustain fire propagation, burning of vegetation (biomass), ignited mostly by lightning strikes and volcanic activity, became an integral part of many global land ecosystems. Humankind evolved alongside naturally occurring fires to eventually develop masterful and extensive techniques of fire management for its benefit. The importance of fire to the development of our species and the societal evolution can hardly be overstated (Gowlett, 2016). Although over time, industrial and, in some parts of the world, domestic use of fire shifted toward other sources of fuel (e.g., coal, oil, and gas), to-date anthropogenic use of fire (biomass burning) continues to present a critical part of life and well-being for people worldwide, a robust landscape management tool, and a potent weapon (Bowman et al., 2011). As anthropogenic use of biomass burning has expanded, humanity's tolerance of naturally occurring fires dwindled, which led to the development of policies and practices in some countries, mostly notably the United States, aimed at near-complete fire suppression about a century ago (Forest History Society, n.d.). The subsequent shift in recent decades toward more severe fires, and a broad appreciation of the value of natural fire to ecosystem health, slowly brought about a more nuanced perspective,

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one that acknowledges fire's benefits within the framework of an adaptive resilience approach (Schoennagel et al., 2017). The perception and acceptance of wildfire, however, have ebbed again as the large number of extreme fire events swept across North America, Southern Europe, Australia, and Northern Eurasia over the last decade. Brought on by the combined impacts of climate (Flannigan et al., 2013) and extensive land-use change (Archibald et al., 2009; Doerr & Santín, 2016), these events have raised concern among policy makers and the general public about the threat to life and economic damage caused by uncontrolled fires. These concerns have grown larger as evidence of negative health outcomes associated with fire-produced air pollutants began to emerge in recent decades.

1.2. CONNECTING THE MODELING CHAIN

Although the number of articles in the scientific literature that examine linkages between air pollution resultant from biomass burning and human health and well-being continues to grow exponentially, this branch of scientific inquiry is still in its infancy partly owing to the complexity of the processes that necessitate a close collaboration between several branches of geophysics and public health fields. The process of establishing and quantifying causal relationships between biomass burning and health outcomes is extremely challenging and requires input from a large number of different experts. Where and when did the fire happen? What was burned and how much? How many pollutants were produced and what kind? How long did they remain the air and how far did they travel? How did they change while they were transported? Who inhaled them and how much? What effect on human bodies do they have? What polices, resources, and intervention strategies are needed to support well-being and resilience to biomass burning? The scope of the inquiry brings together experts in fire ecology, satellite remote sensing, forestry and natural resource management, atmospheric chemistry, atmospheric dynamics, space-time modeling, environmental epidemiology, toxicology, and public health.

The focus of this volume is on describing the observational and modeling approaches that are currently used in fire science, smoke characterization, and health assessment related to biomass burning smoke. The concepts and models that have been developed in these disciplinary camps provide exceptional capability to answer questions and solve problems related to the topic of biomass burning smoke exposure and health. However, their application now is required across the broad transdisciplinary space in order to address a complex set of concerns. And with the transdisciplinary reach of scientific inquiry and modeling efforts comes the necessity of building a foundational understanding of approaches, methods, and tools to craft seamless and robust chains of data analysis. While this foundational understanding is not a substitute for expert knowledge, it will help ensure that the data flow along the modeling chain is not controlled by asking "what we can do" or "what we have always done" in typical siloed approaches but begins solving the more complex interdisciplinary questions of "where are the gaps" and "what and who are needed to fill these gaps". Understanding the fundamental concepts and the limitations of the modeling chain segments will allow research teams to fine-tune their methodological approach at an early stage of inquiry and make research efforts more robust.

1.3. BUILDING A SHARED LANGUAGE

Our diverse international and interdisciplinary community of authors and reviewers highlights the "common language" challenge faced when connecting across established divides. One clear purpose of this book is focused on gaining an improved vocabulary and transdisciplinary knowledge set for considering solutions, which include mitigation actions and adaptive strategies, for avoiding adverse outcomes from biomass burning smoke exposure. The word *fire* is an incredibly commonplace and yet very complicated term. In the *Glossary of Wildfire Terminology* (National Wildfire Coordinating Group, 2021), *fire* is defined as "rapid oxidation, usually with the evolution of heat and light" and while it is technically our subject, the definition is substantially broader than the focus of this book. Here we focus on fires of both natural and anthropogenic origin, intended and unplanned but only those that consume alive and dead plant matter or biomass and occur on the landscape. We thus refer to *fire* here as "biomass burning," a term that incorporates events that can be found in the literature as *wildland fire*, *wildfire*, *bushfire*, *grassland fire*, *peat fire*, *forest fire*, *crop residue fire*, *prescribed fire*, *management fire*, or *landscape fire,* among other terms. While it does capture the absolute majority of potential instances of fire on the land, there are some very important types of fire that we are not considering here. Those include structural fires, trash fires, fossil fuel burning, and any other types of burning of human-made or nonbiomass materials as well as wood-burning for heating and indoor or outdoor cooking. Although all those instances also represent sources of air pollution and richly deserve an in-depth assessment, they are not considered here.

With the widely anticipated increase in biomass-burning driven air pollution during the 21st century (Intergovernmental Panel on Climate Change, 2019), capacity building in assessing the health burden and projecting health outcomes of air pollution arising from biomass burning (natural or anthropogenic) has become not only necessary but also urgent. It takes decades of study and practice to develop sufficient expertise in subfields of each of these broader disciplines. Meanwhile, an interdisciplinary team looking at this subject needs to have basic understanding of fundamental components of the complex process, a scientific equivalent of a common language, to be able to ask the right questions and collaborate effectively or, in the now famous words of Steven Pinker, to connect "the members of a community into an information sharing network with formidable collective powers" (Pinker, 1995, pp. 2–3). Traditionally, successful interdisciplinary teams undergo a multiyear multiproject coevolution where the team members learn these fundamentals through frequent interactions and continuous exposure to ideas and expertise of their collaborators. However, as scientists are challenged with addressing complex and pressing societal issues, streamlining the knowledge base for this subject will pave the way for accelerated interdisciplinary team building.

1.4. STRUCTURE, SCOPE, AND AIMS

In this book we aim to create a foundational knowledge base across a suite of disciplines, which will enable interdisciplinary teams to interact more effectively in addressing impacts of biomass burning air pollution on human health. The book is divided into three sections, which broadly address fire science (Part I: From Fire to Emissions), atmospheric chemistry and dynamics (Part II: From Emissions to Concentrations), and human health research (Part III: From Concentrations to Health Outcomes). Each section contains four chapters, which are designed to cover the foundational knowledge within the field, highlight recent advancements, describe commonly used methods, and outline existing data sets, models, or systems in general use by the respective communities. The three sections of this volume represent three distinct research communities, with members who are often focused on topics adjacent to the topics of fire, smoke, and health. In addition to what is presented here, many other aspects of the broad topic include improvements in geophysical data collection and analysis, predictive and retrospective modeling and data assimilation, as well as socioeconomic aspects of dealing with existing and future biomass burning smoke events. As noted, this is a global problem with far-reaching implications for human health. The chapters here are meant to provide some of the knowledge base for seeding further exploration by the international interdisciplinary community.

The authors have written the text to be comprehensible to experts in the other fields of the modeling chain, with the dual aims of making a subset of this book of value to all experts currently working in this domain, as well as making all components of this book of value to newcomers to the field. Scientific discovery and technological development often outpace the scientific publishing and, thus, books focused exclusively on cutting edge knowledge tend to become outdated before they come out of print. For this book, we include information that will provide the scaffolding for accelerated scientific growth. We have made it a priority to include information that represents the state-of-the-knowledge across the globe with the chapters coauthored and reviewed by members of the international scientific community. However, because we are drawing information exclusively from English-language literature, our scope tends to focus on geographic regions where biomass burning emissions are recognized as a public health concern and covered by research teams that publish their results in English language peer-reviewed journals. Having said that, we believe that the information collected here is applicable to conditions in other geographic regions and should be of help to all national and international scientific and management communities.

1.4.1. Elements of Fire Science

The multiple aspects of fire science (fire ecology, fire behavior, combustion, and more) are studied with a wealth of observational and modeling tools and approaches that draw from extensive field campaigns examining ongoing wildfire and fire management events, surveying post-fire impacts to assess biomass consumption, laboratory and field experiments quantifying consumption and emissions across different types of biomass and under various weather conditions, linking field and laboratory results to satellite observations, and finally convolving the knowledge about properties and spatial extent of biomass burning events and meteorological conditions into emissions modeling (see Part I of this book, "From Fires to Emissions"). Fire regimes (a cumulative description of the frequency, timing, extent, and severity of biomass burning) vary drastically across the globe. Chapter 2, "Biomass Burning as an Integral Force," delves into the mutual impacts of biomass burning, landscape properties, atmosphere, and climate systems that form the basis for understanding when, where, and how biomass burning is likely to impact air quality and how extensive this issue is across various regions of the globe. Much of our current understanding of contemporary fire regimes, the extent of biomass burning events, and our ability to monitor ongoing events globally has been shaped by satellite observations. Chapter 3, "Mapping and Characterizing Fire," describes the kind of information available about biomass burning from Earth observing systems, how this information is extracted, and what gaps and uncertainties these data sets have. However, biomass burning emissions are determined not only by the characteristics of the burning process but also by the composition, structure, and volume of surface fuels. Because fuels are so diverse and complex across global ecosystems, a certain level of standardization and simplification is a must to enable development of modeling approaches. Chapter 4, “Wildland Fuel Characterization Across Space and Time,” synthesizes the current approaches to fuel mapping and highlights remaining gaps and future development needs. Finally, Chapter 5, “Biomass Burning Fuel Consumption and Emissions for Air Quality,” reviews approaches to quantifying how much fuel is consumed during a particular biomass burning event and defining the composition and strength of resultant emissions, generally referred to as smoke.

1.4.2. Elements of Atmospheric Sciences

Biomass burning is a well-known source of gases and particulates that impact the composition of the atmosphere, causing changes in radiative forcing relevant to climate as well as air quality when smoke is found at surface levels (Larsen et al., 2018; Liu et al., 2014). The broad array of methods to sense, model, and map smoke in the atmosphere come out of a rich history of atmospheric science disciplines that include atmospheric physics, dispersion, and chemistry. Part II of the book, “From Emissions to Concentrations,” provides basic concepts of atmospheric smoke concentration sensing, mapping, modeling, and prediction and methods to use information on fire emissions to quantify exposure of people to the pollution resulting from biomass burning. Chapter 6, “Surface Monitoring of Fire Pollution,” provides a broad review of in situ smoke monitoring systems, including advanced sensor networks deployed and maintained by government agencies as well as newer low-cost monitoring technologies that provide data on air pollution concentrations in areas previously void of this information. In Chapter 7, “Data Assimilation for Numerical Smoke Prediction,” concepts behind the methods that use advanced analytical tools to assimilate in situ and remote sensing-based measures of air quality are introduced, providing a glimpse into the complexities of smoke concentration modeling. Chapter 8, “A Review of Modeling Approaches Used to Simulate Smoke Transport and Dispersion,” adds to this by reviewing coupled atmospheric and fire models that allow for integration of fire with atmospheric processes. In Chapter 9, “Profiles of Operational and Research Forecasting of Smoke and Air Quality Around the World,” the various modeling and data assimilation methods are presented in the context of currently operational forecasting systems around the world that are used to inform decisions related to biomass burning smoke encroachment to locations far from the fires themselves. In sum, Part II provides the reader with an understanding of the complexities of smoke concentration mapping and forecasting that help inform decisions and feed knowledge used for assessing biomass burning pollution exposure.

1.4.3. Elements of Health Sciences

The linkage of ambient air pollution exposure with cardiovascular and respiratory morbidity and mortality is well established in the scientific literature (Johnston et al., 2012; Rajagopalan et al., 2018; Schraufnagel et al., 2019a). Studies of additional adverse health effects (i.e., reproductive, perinatal, metabolic, neurological) have accumulated rapidly (Klepac et al., 2018; Schraufnagel et al., 2019b). However, research of physiological and psychological impacts on human well-being specifically related to biomass burning is in its infancy. Part III, “From Concentrations to Health Outcomes,” describes the current state of research, highlights important gaps, and provides guidance for building an interdisciplinary body of work specific to biomass burning risk and exposure assessment, toxicology, and life-span epidemiology. This section is particularly aimed at providing an overview of biomass burning health research findings and needs to (1) promote collaborations between the fire science and smoke modeling communities with health researchers and (2) draw the attention of the ambient air pollution health researchers to the unique and complex issues specific to biomass burning. Chapter 10, “Assessing Smoke Exposure in Space and Time,” provides a general introduction to biomass burning and health research with a focus on exposure and risk assessment science, providing useful paradigms to guide future work. Moving toward more etiologic questions, Chapter 11, “Wildfire Smoke Toxicology and Health,” outlines foundational principles of exposure science and toxicology, and describes the complexities and questions particular to the investigation of human health effects from biomass burning. Chapters 12, “Wildfire Smoke Exposures and Adult Health Outcomes,” and 13, “Health Effects of Wildfire Smoke During Pregnancy and Childhood,” summarize current findings from the limited epidemiologic literature particular to biomass burning, while drawing from the larger body of evidence on the impacts of particulate matter exposures to highlight potential pathways for future work. Chapter 13 is focused on perinatal and early life impacts, and Chapter 12 addresses adulthood.

1.4.4. Geospatial Science Elements

Space-time modeling (a component of geospatial data science) provides a common structure for linking our three subjects of biomass burning, smoke concentration, and exposure of human populations to smoke. Although we do not have a separate section devoted to the geospatial data science elements, various aspects of this rapidly evolving field, from satellite monitoring of biomass burning and atmospheric composition to models of atmospheric dispersion to spatially explicit assessments of vulnerable populations, play a crucial role in enabling this research agenda. Concepts of geospatial data science are not only central to the individual fields of inquiry we are considering in this book but also are absolutely essential for linking these three heretofore disparate topics. The development of powerful tools for studying spatiotemporal subjects in the past three or so decades introduced a mechanism to effectively connect the modeling chain. Despite the general applicability of geospatial methods and modeling approaches among the three fields, the specifics of spatial and temporal scales, sources of error and uncertainties, and overall suitability or compatibility of deliverables for specific studies vary greatly and are not well understood by scientists outside the specific communities. One of our implicit goals in preparing this book was to highlight not only the tremendous opportunities afforded by the contemporary models but also to outline their limitations. While most scientists are acutely aware of how uncertain the information provided by modeled and remotely sensed data sets is within their field, by and large, they are nearly completely blind to accuracy and reliability of data sets emerging from other disciplines. With the exponential growth of geospatial data sets and methods, development of deep understanding of uncertainties across the entire modeling chain is entirely unfeasible. However, a general awareness of where the greatest errors and uncertainties are likely to emerge within this very long chain is of paramount importance in building the most robust scientific inquiry that can support meaningful policy development.

1.5. CONCLUSION

This book presents the first attempt to build a common base for a multidisciplinary community of researchers and practitioners who strive to understand the impact of biomass burning on health and well-being of people worldwide. Individual chapters introduce core concepts, principles, methods, and terminology across a suit of disciplines to bolster multidisciplinary team engagement and raise the starting point for scientific inquiry. Our ultimate goal is to flatten the learning curve and accelerate the rate of knowledge building across various disciplines to enable the experts from various domains speak a common language based upon common understanding. But this book is only the beginning. There are still many concepts, methods, and considerations that we did not cover, and more knowledge is emerging every day. With the observed and expected trends of increased biomass burning under the ongoing and anticipated climate change and the land management projections, associated air pollution will continue to gain prominence as an environmental health hazard. This is the first step toward bringing experts together, making sure that all expertise needed is at the table, and starting the conversation at the next level, asking more sophisticated questions, and building more robust methodologies to enable the strongest possible science.

REFERENCES

Archibald, S., Roy, D. P., van Wilgen, B. W., & Scholes, R. J. (2009). What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology*, *15*(3), 613–630.

Bowman, D. M., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'Antonio, C. M., et al. (2011). The human dimension of fire regimes on Earth. *Journal of Biogeography*, *38*(12), 2223–2236.

Doerr, S. H., & Santín, C. (2016). Global trends in wildfire and its impacts: Perceptions versus realities in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 20150345.

Flannigan, M., Cantin, A. S., De Groot, W. J., Wotton, M., Newbery, A., & Gowman, L. M. (2013). Global wildland fire season severity in the 21st century. *Forest Ecology and Management*, *294*, 54–61.

Forest History Society (n.d.). *U.S. Forest Service fire suppression*. https://foresthistory.org/research-explore/us-forest-service-history/policy-and-law/fire-u-s-forest-service/u-s-forest-service-fire-suppression/#:~:text=In%201933%2C%20the%20federal%20government,day%20following%20its%20initial%20report.

Glasspool, I. J., Edwards, D., & Axe, L. (2004). Charcoal in the Silurian as evidence for the earliest wildfire. *Geology*, *32*(5), 381–383.

Gowlett, J. A. (2016). The discovery of fire by humans: A long and convoluted process. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 20150164.

Intergovernmental Panel on Climate Change (2019). *Summary for policymakers*. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf

Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., et al. (2012). Estimated global mortality attributable to smoke from landscape fires. *Environmental Health Perspectives*, *120*(5), 695–701.

Klepac, P., Locatelli, I., Korošec, S., Künzli, N., & Kukec, A. (2018). Ambient air pollution and pregnancy outcomes: A comprehensive review and identification of environmental public health challenges. *Environmental Research*, *167*, 144–159.

Larsen, A. E., Reich, B. J., Ruminski, M., & Rappold, A. G. (2018). Impacts of fire smoke plumes on regional air quality, 2006–2013. *Journal of Exposure Science and Environmental Epidemiology*, *28*(4), 319–327.

Liu, Y., Goodrick, S., & Heilman, W. (2014). Wildland fire emissions, carbon, and climate: Wildfire-climate interactions. *Forest Ecology and Management*, *317*, 80–96.

National Wildfire Coordinating Group (2021). NWCG glossary of wildland fire, *PMS 205*. https://www.nwcg.gov/publications/pms205

Pinker, S. (1995). *The language instinct: The new science of language and mind* (Vol. *7529*): U.K.: Penguin.

Rajagopalan, S., Al-Kindi, S. G., & Brook, R. D. (2018). Air pollution and cardiovascular disease: JACC state-of-the-art review. *Journal of the American College of Cardiology*, *72*(17), 2054–2070.

Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., et al. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences*, *114*(18), 4582–4590.

Schraufnagel, D. E., Balmes, J. R., Cowl, C. T., De Matteis, S., Jung, S.-H., Mortimer, K., et al. (2019a). Air pollution and noncommunicable diseases: A review by the Forum of International Respiratory Societies' Environmental Committee, Part 1: The damaging effects of air pollution. *Chest*, *155*(2). https://doi.org/10.1016/j.chest.2018.10.042

Schraufnagel, D. E., Balmes, J. R., Cowl, C. T., De Matteis, S., Jung, S.-H., Mortimer, K., et al. (2019b). Air pollution and noncommunicable diseases: A review by the Forum of International Respiratory Societies' Environmental Committee, Part 2: Air pollution and organ systems. *Chest*, *155*(2), 417–426.