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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.

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