IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

A transdisciplinary approach to understanding the health effects of wildfire and prescribed fire smoke regimes

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 Environ. Res. Lett. 11 125009

(http://iopscience.iop.org/1748-9326/11/12/125009)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 210.77.64.106
This content was downloaded on 11/04/2017 at 06:16

Please note that terms and conditions apply.

You may also be interested in:

Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure
Shannon N Koplitz, Loretta J Mickley, Miriam E Marlier et al.

Measurement of inter- and intra-annual variability of landscape fire activity at a continental scale: the Australian case
Grant J Williamson, Lynda D Prior, W Matt Jolly et al.

Sensitivity of mesoscale modeling of smoke direct radiative effect to the emission inventory: a case study in northern sub-Saharan African region
Feng Zhang, Jun Wang, Charles Ichoku et al.

Future respiratory hospital admissions from wildfire smoke under climate change in the Western US
Jia Coco Liu, Loretta J Mickley, Melissa P Sulprizio et al.

Objective identification of multiple large fire climatologies: an application to a Mediterranean ecosystem
J Ruffault, V Moron, R M Trigo et al.

Does chronic nitrogen deposition during biomass growth affect atmospheric emissions from biomass burning?
Michael R Giordano, Joey Chong, David R Weise et al.

Future changes in climatic water balance determine potential for transformational shifts in Australian fire regimes
Matthias M Boer, David M J S Bowman, Brett P Murphy et al.

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
29 May 2016

REVISED
23 October 2016

ACCEPTED FOR PUBLICATION
2 November 2016

PUBLISHED
6 December 2016

Original content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

LETTER

A transdisciplinary approach to understanding the health effects of wildfire and prescribed fire smoke regimes

G J Williamson[1], **D M J S Bowman**[1], **O F Price**[2], **S B Henderson**[3] and **F H Johnston**[4,5]

1 School of Biological Sciences, University of Tasmania, Hobart, Tasmania, Australia
2 School of Biological Sciences, University of Wollongong, Wollongong, New South Wales, Australia
3 British Columbia Centre for Disease Control, Vancouver, British Columbia, Canada
4 Menzies Research Institute, University of Tasmania, Hobart, Tasmania, Australia
5 Author to whom any correspondence should be addressed.

E-mail: Fay.Johnston@utas.edu.au

Keywords: smoke, prescribed fire, wildfire, health, review, management

Abstract

Prescribed burning is used to reduce the occurrence, extent and severity of uncontrolled fires in many flammable landscapes. However, epidemiologic evidence of the human health impacts of landscape fire smoke emissions is shaping fire management practice through increasingly stringent environmental regulation and public health policy. An unresolved question, critical for sustainable fire management, concerns the comparative human health effects of smoke from wild and prescribed fires. Here we review current knowledge of the health effects of landscape fire emissions and consider the similarities and differences in smoke from wild and prescribed fires with respect to the typical combustion conditions and fuel properties, the quality and magnitude of air pollution emissions, and the potential for dispersion to large populations. We further examine the interactions between these considerations, and how they may shape the longer term smoke regimes to which populations are exposed. We identify numerous knowledge gaps and propose a conceptual framework that describes pathways to better understanding of the health trade-offs of prescribed and wildfire smoke regimes.

Introduction

Landscape fire smoke is a complex and dynamic mix of energy, water vapour, gases, and aerosols. Gaseous emissions affect climate forcing and biogeochemical cycling, while aerosols affect rainfall distribution and warming of the troposphere (Langmann *et al* 2009) and transport of plant nutrients. The public health impacts of air pollution, including landscape fire smoke, have become more clearly characterised over recent decades (Reid *et al* 2016a, 2016b). Globally, an estimated three million deaths each year are attributable to outdoor air pollution (Lim *et al* 2013), while an estimated 340 000 annual deaths are attributable to smoke from landscape fires (Johnston *et al* 2012). Even when fires do not cause loss of infrastructure or direct human injury, large human populations can be exposed to smoke pollution causing measurable increases in mortality and morbidity (Henderson *et al* 2011, Faustini *et al* 2015, Adetona *et al* 2016), such that including the health impacts of smoke changes the overall economic burden of wildfire events (Johnston and Bowman 2014).

Fire is an inevitable feature of many environments on Earth, yet humans are able to manipulate landscape fire activity for a diversity of reasons (Bowman *et al* 2011). A key technique is intentionally burning landscapes to reduce fuel loads and hence the occurrence, extent, and severity of uncontrolled wildfires (Fernandes and Botelho 2003). When appropriately planned, escape of prescribed fires from intended boundaries occurs in less than 1% of cases (Dether and Black 2006), but when escapes occur they can result in significant damage to homes and infrastructure (Smith 2012). In many jurisdictions, smoke management is an important constraint on prescribed burning (Sneeuwjagt *et al* 2013) leading to an unresolved policy debate about human health trade-offs between smoke from wildfire and prescribed fires. This problem involves numerous disciplines including

© 2016 IOP Publishing Ltd

epidemiology, meteorology, atmospheric chemistry, fire ecology and management, but few researchers or practitioners have such transdisciplinary expertise. Our objective is to provide a succinct review of this complex problem and to propose a conceptual transdisciplinary framework that can be used to guide further research.

Smoke impacts on human health

The health impacts of landscape fire smoke are driven by: (1) chemical composition and concentrations of pollutants in the smoke plume; (2) the intensity and duration of the smoke exposure during an event; (3) the extent to which individuals can protect themselves from the exposure and (4) the number of individuals who are exposed and their underlying health status.

The epidemiologic literature has focussed on concentrations of particulate matter less than 2.5 microns in diameter ($PM_{2.5}$), which is routinely measured and has been widely studied (Pope and Dockery 2006). Exposure to $PM_{2.5}$ from many different sources has a range of impacts on human physiology, including: promotion of inflammation and blood coagulation; impairment of the respiratory, cardiovascular, and autonomic nervous systems; and increased risk of genetic mutations (Brook *et al* 2004, Barregard *et al* 2006, Berhane *et al* 2011, Danielsen *et al* 2011). Although the composition of PM2.5 can vary widely, there is insufficient evidence to quantify the relative influence different chemical compositions on health outcomes at this time (Levy *et al* 2012). In a healthy person, short term physiological changes in response to $PM_{2.5}$ are unlikely to be of clinical importance, yet they can pose significant risk to unhealthy people. For instance, increased concentrations of $PM_{2.5}$ may precipitate heart attack or stroke in a person who already has cardiovascular disease, potentially leading to death (Brook *et al* 2004). Likewise, smoke exposure might cause minor irritation of the eyes or throat in healthy people, but could precipitate severe breathing difficulty in a person with asthma or other respiratory disease (Johnston *et al* 2006). Positive associations between forest fire smoke and mortality have been documented in a range of settings including Europe (Faustini *et al* 2015), Russia (Shaposhnikov *et al* 2014), south-eastern Australia (Johnston *et al* 2011a, 2011b) and Malaysia (Sastry 2002). The population health impacts of $PM_{2.5}$ are observed across all $PM_{2.5}$ concentrations with no safe threshold, which highlights the potential impacts of prescribed fires, even though they produce comparatively less smoke than wildfires.

Although serious health outcomes are relatively rare, the absolute number of people who suffer serious impacts from smoke events can be substantial when large populations are exposed. The health impacts of air pollution are tied to the prevalence of risk factors in the population, such as cardiovascular and lung diseases, diabetes, older or younger age, and lower socioeconomic backgrounds (Eze *et al* 2015, Pope *et al* 2011). The same is likely true for fire smoke, although there has been less research on the topic (Reid *et al* 2016a, 2016b). Smoke exposure is known to disproportionately affect people with lung diseases (Henderson and Johnston 2012) and the evidence concerning impacts on heart diseases is emerging (Rappold *et al* 2012, Haikerwal *et al* 2015a, 2015b). A few studies have also demonstrated adverse impacts on infants and unborn babies (Jayachandran 2009, Holstius *et al* 2012), and on people with lower socioeconomic status (Reid *et al* 2016a, 2016b Environmental Research, Rappold *et al* 2012). Higher adverse health outcomes from smoke exposure have also been documented for Indigenous Australians who have worse population health outcomes compared with non-Indigenous people (Johnston *et al* 2007, Hanigan *et al* 2008).

Some of the adverse health effects of smoke can be mitigated through preventative medication (Bhogal *et al* 2006). By definition, preventive medication must be taken in advance to reduce the likelihood of deterioration in symptoms (National Asthma Council Australia 2015), and this requires advanced notice of possible smoke impacts. Similarly, short-term reduction of personal exposure to smoke in homes can be achieved if doors and windows are closed before a smoke event. In an open house, indoor air quality will rapidly reflect outdoor conditions (Dix-Cooper *et al* 2014). There is evidence that creating clean air refuges using mechanical air filtration substantially reduces wildfire smoke exposure (Barn *et al* 2008, 2016). However, such devices have not been widely adopted. Moving people to areas unaffected by smoke is logistically challenging and stressful for the affected populations. The only evaluation of evacuation during severe smoke events concluded that it was protective in only 30% of cases (Krstic and Henderson 2015). Specialised face-masks can be effective in occupational settings for personal protection, however there is no evidence these are helpful as a public health protection measure for wildfire smoke episodes (Sbihi *et al* 2014).

Wild and prescribed fires generally result in different smoke exposures to human populations. Wildfires are unpredictable and, in temperate forest ecosystems, can occur at a low frequency (decades) whereas prescribed burning is more predictable and can occur at a greater frequency. Thus wildfire smoke affects large areas and potentially large populations, contrasted with the potential for severe local impacts of prescribed fire smoke (Haikerwal *et al* 2015a, 2015b). The relative health effects of these contrasting smoke exposures remain unknown. An additional research challenge lies in understanding the contribution of background air pollution from other sources, which complicates resolving the relative effects of wildfire and prescribed fire smoke.

Biomass combustion and smoke production

Differences in fire intensity, area burnt, fuel availability and type, and duration of fires all affect smoke volume, composition and dispersion. Large wildfires tend to occur during drought periods and in severe fire weather, driven by high temperatures, low relative humidity, and strong winds (Meyn *et al* 2007). This results in the combustion of larger fuels, with the potential to spread to the canopies of woody vegetation (Wagner 1977). By contrast, prescribed fires are typically lit during milder weather, which results in the combustion of fine surface fuels and limited damage to forest canopies (Agee and Skinner 2005). Complex physiochemical processes of pyrolysis and combustion involving the breakdown of hydrocarbons drive qualitative and quantitative differences between wild and prescribed fire smoke.

Pyrolysis involves heating fuel to enable the endothermic reactions that break up long chain hydrocarbons to produce solids and gases, and vaporise the moisture in the fuel (Sullivan and Ball 2012). Many of the gaseous compounds are strong greenhouse gases (Jain *et al* 2006) and can be toxic to humans (Demling 2008). Combustion is a rapid exothermic oxidation of the products of pyrolysis that releases energy in the form of heat and light. Idealised complete combustion is a process where all hydrocarbons in the original fuel, both gaseous and solid, combine with oxygen to release energy and form carbon dioxide (CO_2) and water vapour (H_2O) (Rein 2013). In all landscape fires, combustion is incomplete, producing a smoke that includes gases (CO_2, CO, H_2O, NO_x, NH_4, SO_x, CH_4, phenols, etc) and aerosols (elemental, organic, and inorganic carbon compounds)(Akagi *et al* 2011). While many of these species are also harmful to human health, the population level impacts are primarily driven by the concentrations of aerosols measured as $PM_{2.5}$ (Reisen *et al* 2015). The combustion process also liberates small quantities of macro and micro plant nutrients and trace elements, including heavy metals. Constituent compounds in the smoke can undergo further chemical transformation in the atmosphere after emission, while aging can also alter aerosol size, composition, and concentration (Cubison *et al* 2011). In general, the concentration of $PM_{2.5}$ is thought to scale with the concentrations of the co-occurring organic and inorganic compounds (Ward *et al* 1996, Andreae and Merlet 2001).

The enormous variability in smoke composition is due to the substrate burned and factors that determine the completeness of oxidation during combustion, including the fuel moisture content, temperature of combustion, and amount of oxygen available (Hobbs *et al* 1996). Combustion is often divided into high-temperature flaming and low-temperature smouldering types to differentiate the chemical processes and the smoke emissions. Flaming is produced by the combustion of gases, which is rapid and involves more complete consumption of the original fuel. Smouldering is produced by the combustion of solids, which is slower and less complete. Flaming versus smouldering combustion is one of the most important determinants of potential public health impacts, because smouldering and incomplete combustion greatly increases the emissions, the suite of toxic co-pollutants, and the burn duration (Bertschi *et al* 2003, Janhäll *et al* 2010, Reisen *et al* 2015). Many factors affect the relative proportions of flaming and smouldering combustion in a landscape fire, including the temperature of combustion (Einfeld *et al* 1991), the fuel moisture, mass and composition of the fuel (such as grass, wood, or peat), and the stage of the fire (Surawski *et al* 2015). In a fuel bed with high moisture content, the heat released by flaming combustion is often used to vaporise water in nearby fuel particles. In a fuel bed with low moisture content, combustion is more rapid and complete due to the maintenance of higher temperatures, promoting the combustion of the volatile compounds and gases. These factors are shaped by the current and antecedent meteorological conditions (Weise and Wright 2014).

Weather conditions have major influences on fire behaviour and smoke production, and fire weather is increasingly studied at a global scale (Field *et al* 2015, Jolly *et al* 2015). Relative humidity and rainfall drive landscape fuel moisture, while wind speed drives oxygen delivery and energy transport, which dictate the speed and completeness of combustion, as well as the rate of fire spread (Rothermal 1983, Dowdy *et al* 2010). The spatial arrangement of the fuel array also influences oxygen availability, the completeness of the combustion process, and hence the composition of emissions (Weise and Wright 2014). Densely packed fuels allow little oxygen penetration and slower, less complete combustion. Larger fuels, such as branches and logs, have lower surface-area-to-volume ratios that reduce oxygen penetration. These fuel types often undergo extended smouldering combustion rather than rapid flaming combustion. For all of the above reasons the leading fire front often features more efficient flaming combustion, while smouldering combustion dominates the flanks (Surawski *et al* 2015).

Assigning emissions factors to strict prescribed or wildfire categories is complicated by the range of variables driving smoke production. For example, prescribed fires may be carried out in moister fuels, leading to less efficient and greater smouldering combustion. They are also less likely to burn heavy fuels, such as logs, that may smoulder for a long time (Bertschi *et al* 2003). Wildfires typically have a mix of flaming fires (at the head of the fire) and smouldering fires (on the flank of the fire). Improved physical models of pyrolysis, fuel consumption and spread dynamics may be required to accurately establish smoke constituents under different burning conditions and fire behaviours.

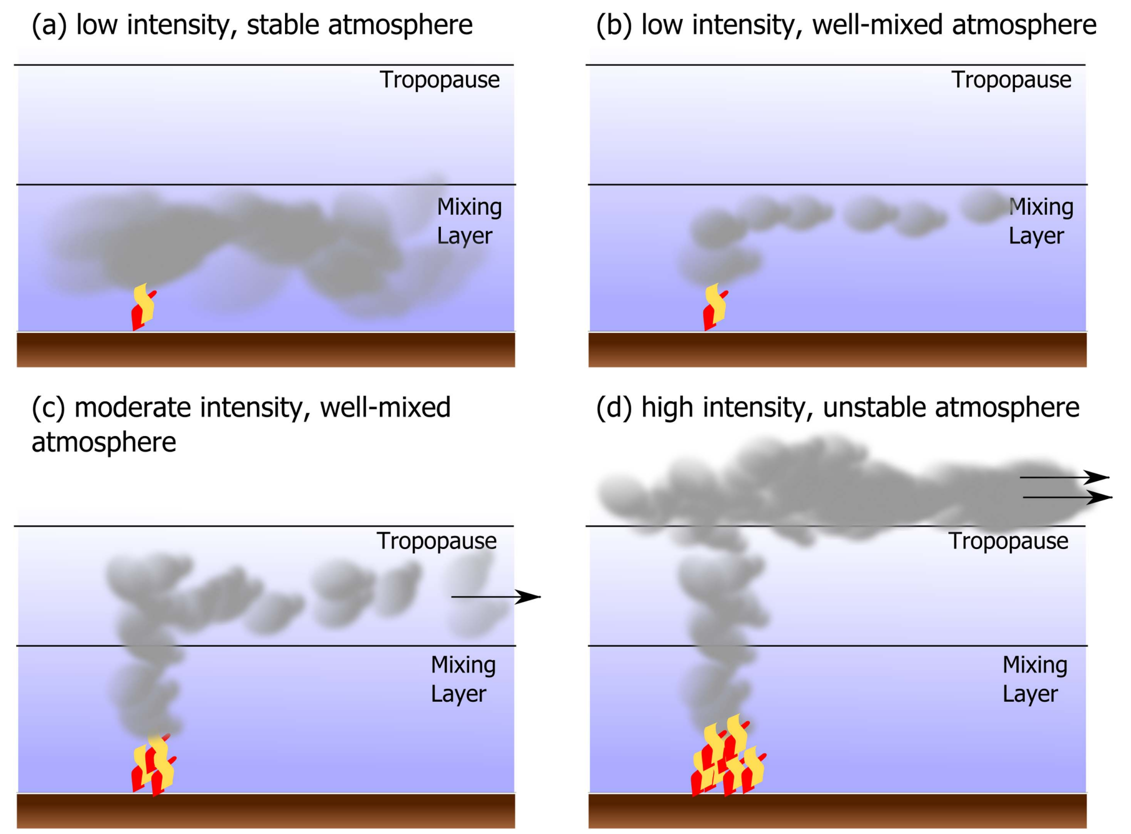

Figure 1. Examples of smoke dispersion under a variety of atmospheric conditions and fire intensities: (a) a low intensity fire in a pronounced inversion or stable atmosphere produces smoke that is restricted to bottom of the mixing layer; (b) a low intensity fire in a well-mixed atmosphere produces smoke that is transported regionally below the mixing layer; (c) a moderately intense fire in a well-mixed atmosphere produces smoke that penetrate through the mixing layer enabling long distance (100 kms) transport in the upper troposphere; and (d) a high intensity fire in an unstable atmosphere produces smoke that penetrate the stratosphere and disperses at a global scale.

Smoke transport

Smoke transport is shaped by many complex interactions between landscape fire and meteorological conditions, with the most critical determinant being the injection height, at which horizontal transport of the plume begins. Smoke plumes with low injection heights will disperse within the mixing layer, the lower layer of the atmosphere in contact with the Earth's surface, while smoke plumes with high injection heights may be carried aloft over long distances by winds in the upper atmosphere (figure 1). There is a broadly linear association between fire intensity (total instantaneous energy release) and plume height (Val Martin *et al* 2009, Raffuse *et al* 2012, Peterson *et al* 2014), because the rate of biomass consumption drives the rate of heat release. In turn, the rate of heat release drives the plume buoyancy, such that intense, hot fires create a convection column and high injection heights (Fromm *et al* 2006). Intense wildfires are associated with higher injection heights than lower intensity prescribed fires, which are assumed to produce lower smoke plumes, as is the case with agricultural fires that have low fuel loads (Kaskaoutis *et al* 2014). The locality of impact from different fire types can be expected to be correlated with injection height, and therefore fire intensity, with lower intensity fires more likely to impact local communities and high intensity fires resulting in broader long-range but more diffuse population impacts.

The atmospheric stability and mixing height (the height above ground in which turbulence produces well-mixed air) also determines how well smoke can be dispersed (figure 1). A stable atmosphere occurs when air temperatures decrease slowly with height, whereas an unstable atmosphere occurs when temperatures decrease rapidly with height (Ferguson 2001). For example, Boer *et al* (2009) found increased particulate pollution in cities surrounded by prescribed fires set under stable, low wind-speed conditions. Unstable atmospheric conditions can contribute to extremely intense and uncontrollable fires (Trentman *et al* 2006, Cruz *et al* 2012, McRae *et al* 2015) and convection columns that can penetrate past the mixing layer, even reaching into the stratosphere. This smoke often has minimal local impacts relative to the size of the fire, but the aerosols in the upper atmosphere have a significant climate impact (Westphal and Toon 1991), and they can be transported around the globe to have impacts in other areas (Sapkota *et al* 2005).

The ability for the atmosphere to disperse smoke can be captured by the ventilation index (VI, Goodrick *et al* 2013), which multiplies the mixing height and the mean wind speed. This index can be used to plan optimum conditions for prescribed fire to ensure smoke transport away from local communities, and is applied in this capacity in British Columbia. High VI values indicate a high mixing height and wind speed, with good smoke dispersion conditions. Low VI values indicate a low mixing height and still air, often resulting in temperature inversions where pollution is trapped in a cold layer of air near the surface. Smoke impacts are often highest during stable atmospheric conditions and temperature inversions that form under meteorological conditions suited to prescribed burning (Price *et al* 2016). The atmospheric dispersion index (ADI, Lavdas 1986, Goodrick *et al* 2013) builds on the ventilation index by adding a measure of atmospheric stability in predicting smoke dispersion capability, and variants on this index is used in several jurisdictions in the United States to inform planned burn planning. Evaluation of these simple dispersion indices as an alternative to computationally intensive smoke modelling is an important avenue for future research.

Health and prescribed and wildfire 'smoke regimes'

We suggest that smoke emissions from wild and prescribed fires can be conceptualised as a smoke regime in the same way that fire ecologists integrate the effects of recurrent fires under the rubric of the fire regime. Understanding the totality of the health effects of a smoke regime from prescribed and wildfires requires considering numerous trade-offs. The increased fraction of fuel burnt in wildfires produces more smoke emissions. Williamson *et al* (2013) found the mean horizontal footprint of wildfire plumes to be six times greater than those for prescribed fires in south-eastern Australia. However, the higher intensity of wildfires means the greater likelihood of plumes reaching the upper atmosphere, where horizontal transport can carry the smoke away from the local area. Prescribed fires can be planned, to some extent, around optimal atmospheric conditions for smoke transport, but the lower intensity of the fire can result in lower atmospheric injection heights and greater local impacts on air quality. In particular, prescribed burns must avoid hot and windy conditions in favour of cool, still days to minimise the risk of fires escaping planned boundaries. This inevitably means that prescribed fires often coincide with overnight temperature inversions that trap smoke in valleys where people often live.

Prescribed burns may cause a negative feedback on subsequent wildfire area and intensity, but the nature of this feedback can only be quantified over the long term, via the influence of a prescribed burning program on the fire regime of an area. Empirical and simulation studies have shown that prescribed burning reduces the area of wildfire in the forests of southern Australia by a ratio of approximately one third, meaning each one-hectare reduction in wildfire are requires a three-hectare area of treatment (Boer *et al* 2009, Price and Bradstock 2011, Bradstock *et al* 2012b). This ratio has been termed 'leverage' (Loehle 2004, Price *et al* 2015). In non-forest regions with lower fuel loads and less frequent wildfire, the leverage is even lower (Price *et al* 2012a, Price *et al* 2015). Only in regions with particularly high fire frequency, such as savannas, can a 1:1 ratio be achieved (Vilen and Fernandes 2011, Price *et al* 2012b). The implication is that prescribed burning programs will increase the overall area burnt in most regions. The inefficiency of prescribed fires at reducing wildfire area is because fuels recover quickly and wildfires are rare, such that most fuel-reduced patches are not encountered by a wildfire. If a wildfire does encounter a treated patch the intensity is reduced, which implies lower fuel consumption and smoke emission but the effects have never been quantified with respect to intensity, fuel consumption or smoke. Instead, studies have focussed on the reduction of fire severity, a measure of crown scorch (Keely 2009), which can be mapped using post-fire remote sensing. These studies have demonstrated that recent prescribed burning reduces damage to the forest crown, but the effect decreases as the time-since-fire increases and as the fire weather becomes more severe (Bradstock *et al* 2010, Price and Bradstock 2012, Tolhurst and McCarthy 2016). To quantify the full effect of a prescribed burning program on smoke pollution requires the integration of the leverage effect and the reduction in intensity effect. Bradstock *et al* (2012a) explored this integration in the context of predicting greenhouse gas emissions, concluding that prescribed burning programs were unlikely to reduce emissions, while acknowledging that a definitive answer depends on gathering empirical evidence on fuel consumption by prescribed and wildfire.

Given the mechanisms of feedback between prescribed and wildfire, community smoke exposure can only be compared by considering the smoke regime rather than emissions from individual fires, in other words, smoke from more frequent and less severe fires versus smoke from less frequent more severe fires. For example, Schweizer and Cisneros (2016) argue that smoke regimes in the USA would be less harmful to public health with a policy of regular prescribed burning than with a policy of total fire suppression. The comparative population health impacts of smoke regimes will be driven mostly by the number and susceptibility of people affected by smoke from each regime. Smaller fires usually have more local impacts while larger fires have greater capacity for long distance transport. Although smoke generation and population exposure might be reduced by smaller fires, the public health costs may be borne by populations that are repeatedly exposed to smoke from a local regime of prescribed fire. This may be further complicated by climate change, which is reducing the window of opportunity for prescribed burning each year and leading to more fires being set when the conditions are favourable. This compression can result in pollution events as severe as those associated with larger wildfires, exemplified by the conditions in Sydney during May 2016 (figure 2).

Modelling population exposure to smoke

Modelling smoke production and transport is critical for predicting and modelling smoke exposure from wild and prescribed fires. This is challenging because of the need to parameterise fuel type and mass, rate of and type of consumption, and energy release and atmospheric conditions (Heilman *et al* 2014).

The direct measurement of smoke emissions is constrained by the availability air monitoring stations, and a dense network is required for tracking and understanding dispersion. Routine monitoring is often biased towards large urban or industrial centres, with a focus on mobile and industrial sources for regulatory purposes (Johnston *et al* 2010). Increasingly, however, smoke monitoring networks based on large numbers of inexpensive, spatially dispersed, real time instruments are being deployed. Such networks help to improve smoke dispersion models and to quantify community impacts more meaningfully. Examples include the Florida Air Quality System (FLAQS, www.dep.state.fl.us/Air/air_quality/airdata.htm) and the Base Line Air Network of EPA Tasmania (BLANkET, http://epa.tas.gov.au/epa/real-time-air-quality-data-for-tasmania). These networks can also provide real-time data on smoke impacts to the public. An alternative to ground-based particle monitors are remote sensing platforms on satellites, which can measure atmospheric aerosol concentration over large geographic areas. Data products such as the aerosol optical depth (AOD) or aerosol optical thickness (AOT) measure total atmospheric aerosol by comparing the scattering of light in a given pixel with its spectral signature under a low aerosol load. While AOD measures particles throughout the atmospheric column, there is often strong correlation with particulate concentrations at ground level (van Donkelaar *et al* 2015). These measurements are available in areas outside the ground-based monitoring network, allowing quantification of long-distance smoke transport. The polar-orbiting MODIS, AVHRR and VIIRS instruments all provide AOD measurements at varying resolutions and overpass frequencies, while geostationary satellites, including GOES satellites over the Americas and the Himawari-8 satellite over east Asia, also provide continuous AOD coverage. Other instruments use LiDAR (e.g. CALIOP) or stereoscopic imagery (e.g. MISR) to provide three-dimensional imagery of smoke plumes.

Goodrick *et al* (2013) provide an excellent review of the range of empirical and physical models available for smoke dispersal. Empirical models use statistical relationships to describe observed smoke concentrations with respect to a range of predictor variables associated with smoke emissions including land use, meteorology, satellite location of fire and estimates of intensity. For example, Yao and Henderson (2014) developed a system for British Columbia, Canada that incorporates MODIS AOD, atmospheric venting index, measured $PM_{2.5}$, and MODIS fire radiative power measurements to estimate smoke concentrations across the province. There was a correlation coefficient of 0.84 between model estimates and observed $PM_{2.5}$ concentrations in training cells on high-smoke concentration days. These models are simple to parameterise and require little computational power, but are often only locally applicable and can perform poorly in conditions outside the training environment. Physical models range in complexity from simple box models, such as the atmospheric dispersion index (ADI), through to grid models with a lattice of cells with pollutant concentrations and meteorological variables (Goodrick *et al* 2013). In between, there are Gaussian plume models, which incorporate wind impacts on plume dispersion, puff models, which disperse independent puffs of smoke with defined pollutant concentrations, and particle models, which simulate the movement of individual particles through the atmosphere. Each approach has particular strengths, weaknesses, and applications.

The most elaborate and potentially useful class of models are gridded numerical chemical transport models, such as the Australian Air Quality Forecasting System (AAQFS, Cope *et al* 2004). These systems incorporate a meteorological model to simulate atmospheric temperature profiles and wind, emissions sources parameterised with emissions factors for a variety of chemical species, and chemical models able to account for changes in chemistry as the smoke ages. Increases in computing power and the greater availability of data sources for validation and model improvement mean that physical models have the potential to improve our prediction of smoke impacts from landscape fire over the coming years. A fusion of multiple approaches is likely to emerge, to develop systems for accurate prediction and estimation of smoke emissions. Such models will not only be pivotal in resolving the trade-offs of wildfire and prescribed fire, but also for providing advanced public health warnings (Yuchi *et al* 2016).

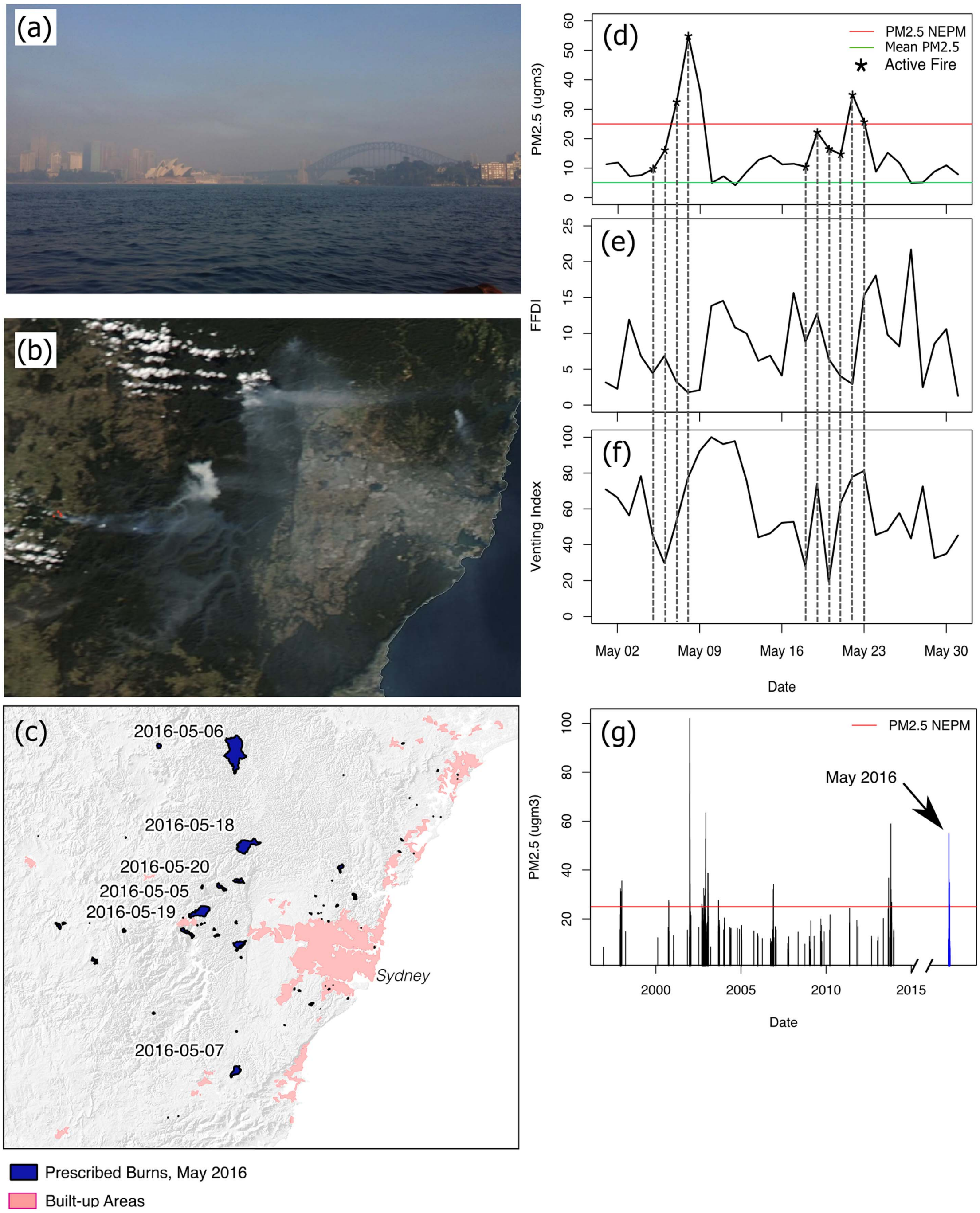

Figure 2. An example from the Sydney basin, which covers an area of ~25 000 km^2 and has a population of approximately 5 million people. In May 2016 prescibed fires were set under low danger conditions to reduce fire hazard. The unintended consequence of this intervention was a smoke pollution event equally as severe as those caused by extreme wildfires in a validated record from 1995 to 2014 (Johnston *et al* 2011a, 2011b, Hanigan *et al* 2016). Panels are as follows: (a) an image of the pollution obscuring the iconic Sydney Harbour Bridge; (b) MODIS imagery from the Aqua satellite on May 22 2016 showing the extent of the smoke pollution from the prescribed fires to the west of the Sydney Basin; (c) the locations of prescribe fires set during May 2016; (d) the daily average $PM_{2.5}$ concentrations in May 2016 showing exceedences of the the 25 $\mu g\ m^{-3}$ Australian air quality standard (NEPM—National Environment Protection Measure), and long term mean concentration; (e) the daily forest fire danger index (FFDI) in May 2016, showing low risk due to mild weather conditions—values never exceed 25, the 'very high' fire danger category; (f) the daily venting index for May 2016 showing periods of decreased venting during periods of increased burning (low values), which entrapped the smoke; and (g) the PM2.5 during the May 2016 event compared with smoke from some of the most intense wildfire episodes in the previous 20 years, as described in a validated smoke event database for the region (Johnston *et al* 2011a, Hanigan *et al* 2016). Previous epidemiologic studies in the Sydney Basin have shown that smoke events of similar magnitude are associated with additional deaths, admissions to hospital, and presentations to hospital emergency departments (Johnston *et al* 2011a, 2011b, Martin *et al* 2013, Johnston *et al* 2014). Such impacts need to be weighed against the wider impacts and risks of avoiding prescribed burns altogether, or modifying their implementation to reduce the potential for severe smoke events.

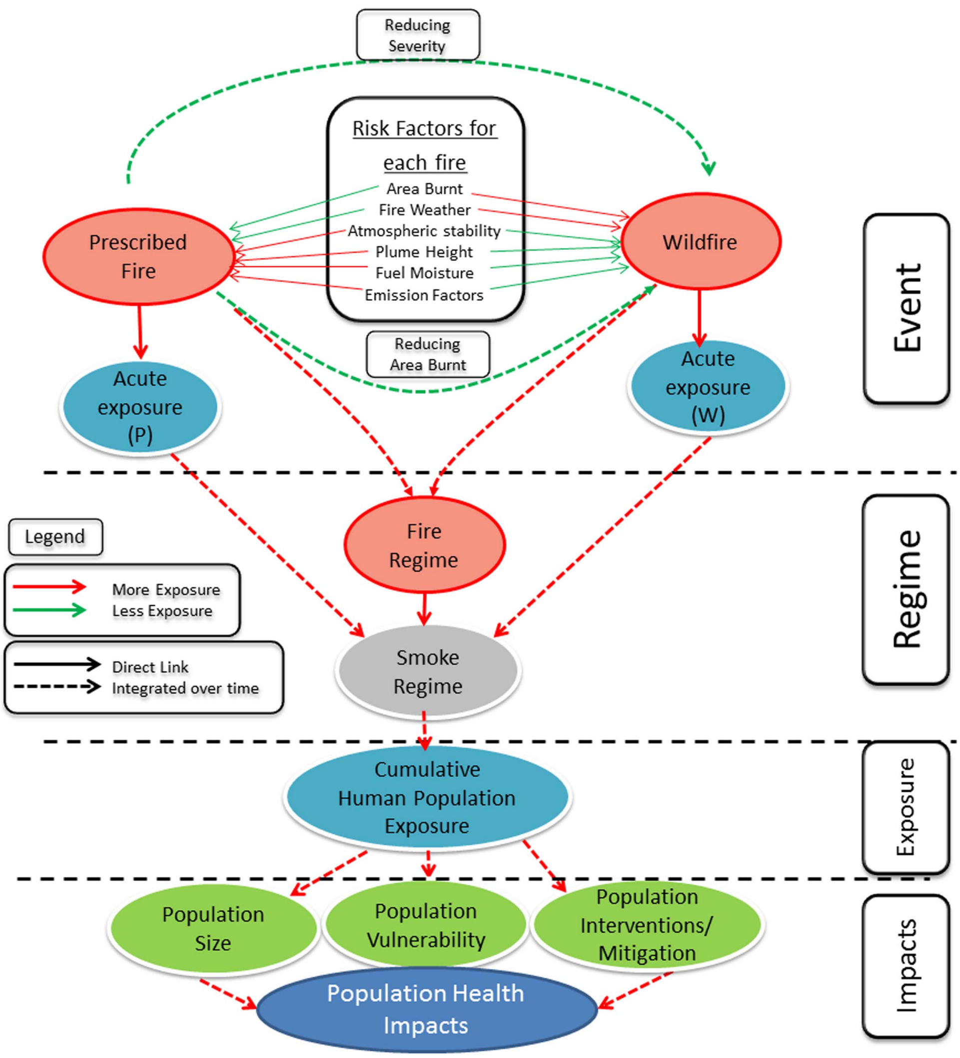

Figure 3. Framework to understand the causes and uncertainties of landscape fire effects on human health. The framework is broken down into events, regimes, exposure, and impacts. Individual fire events have features that can either dampen or amplify smoke production (green and red lines). Smoke and fire regimes are the collective consequences of numerous events. Long-term smoke exposure is shaped by the interaction between fire and smoke regimes. The health impacts of smoke exposure are modulated by the distribution and demographic profile of human populations. The aggregate population health impacts are determined by the complex interaction of all the factors denoted in the diagram. There is no current assessment that considers all factors that influence the health outcomes of prescribed and wildfires. Such analysis is required to better understand the human health trade-offs inherent is the use of planned fire to manage wildfire.

Framework for understanding smoke health impacts of wild and prescribed fires

A range of research challenges in the fields of fire ecology, epidemiology, and atmospheric sciences must be resolved before the relative human health costs of wild and prescribe fire smoke regimes can be accurately estimated. A framework to understand the interrelations among the many complex factors is presented here (figure 3). To understand the full impact of prescribed burning programs on human health we must consider the risk factors for each fire (the event), the feedbacks between prescribed and wildfire over time (the fire and smoke regimes), how this translates into the interaction between smoke and populations (the exposure), and, ultimately the effects of the exposure on the population as a function of its size, vulnerability and preparedness (health impacts). This framework will be useful for developing predictive models of smoke exposure, because understanding exposure is essential for quantifying the health costs of both wild and prescribed fire smoke regimes. Predictive models are also crucial to enable fire managers to reduce smoke exposures and provide warnings to susceptible people.

Conclusion

We have provided a transdisciplinary review of the health impacts of smoke from wild and prescribed fires. This problem demands understanding recent advances in air pollution epidemiology generally, and the specific effects of landscape fire smoke. The composition of landscape fire smoke is extraordinarily complex, and we use $PM_{2.5}$ concentrations as an epidemiologic proxy for the mixture because we have only incipient understanding of its overall toxicology. Modelling of smoke particle emissions demands quantification of the type of fuel and prevailing meteorological conditions, both of which influence the combustion conditions. The likely human health impacts of this smoke depend on the size of populations affected, the concentration and duration of exposure, and the effectiveness of any public health interventions. Prescribed fires can reduce the incidence of wildfires, trading off frequent short-term local-scale smoke pollution events for reductions in longer time-scale broader population exposures. This trade-off must be incorporated into any evaluation of the health impacts for specific smoke regimes but it is impossible to understand the respective health impacts of prescribed and wildfires with the available data. Instead, we propose a structured framework that outlines the necessary steps to move towards resolution of this critical public health issue.

Acknowledgments

The content of this work was based on presentations by FHJ, DMJSB, GJW, and SBH at the symposium 'Finding the Balance' held at the University of British Columbia, April 2016. This public forum about balancing wildfire, prescribed fire, forest health, and public health was sponsored by Health Canada, Wall Institute for Advanced Studies, UBC School of Population and Public Health, UBC Faculty of Forestry, and the British Columbia Centre for Disease Control. We thank the other attendees for their contributions to this work via scholarly dialogue and debate. Our research is also supported by an Australian Research Council Linkage Grant (LLP130100146).

References

Adetona O, Reinhardt T E, Domitrovich J, Broyles G, Adetona A M, Kleinman M T, Ottmar R D and Naeher L P 2016 Review of the health effects of wildland fire smoke on wildland firefighters and the public *Inhalation Toxicology* **28** 95–139

Agee J K and Skinner C N 2005 Basic principles of forest fuel reduction treatments *Forest Ecol. Manag.* **211** 83–96

Akagi S K, Yokelson R J, Wiedinmyer C, Alvarado M J, Reid J S, Karl T, Crounse J D and Wennberg P O 2011 Emission factors for open and domestic biomass burning for use in atmospheric models *Atmos. Chem. Phys.* **11** 4039–72

Andreae M O and Merlet P 2001 Emission of trace gases and aerosols from biomass burning *Glob. Biogeochem. Cycles* **15** 955–66

Barn P, Larson T, Noullett M, Kennedy S, Copes R and Brauer M 2008 Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness *J. Exposure Sci. Environ. Epidemiol.* **18** 503–11

Barn P K, Elliott C T, Allen R W, Kosatsky T, Rideout K and Henderson S B 2016 Portable air cleaners should be at the forefront of the public health response to landscape fire smoke Submitted to *Environ. Health*

Barregard L, Sallsten G, Gustafson P, Andersson A, Johansson L, Basu S and Stigendal L 2006 Experimental exposure to wood-smoke particles in healthy humans: effects on markers of inflammation, coagulation, and lipid peroxidation *Inhal. Toxicol.* **18** 845–63

Berhane K, Zhang Y, Linn W S, Rappaport E B, Bastain T M, Salam M T, Islam T, Lurmann F and Gilliland F D 2011 The effect of ambient air pollution on exhaled nitric oxide in the Children's Health Study *Eur. Respiratory J.* **37** 1029–36

Bertschi I, Yokelson R J, Ward D E, Babbitt R E, Susott R A, Goode J G and Hao W M 2003 Trace gas and particle emissions from fires in large diameter and belowground biomass fuels *J. Geophys. Res.: Atmos.* **108** 8472

Bhogal S, Zemek R and Ducharme F 2006 Written action plans for asthma in children *The Cochrane Database of Systematic Reviews* (3): CD005306

Boer M M, Sadler R J, Wittkuhn R S, McCaw L and Grierson P F 2009 Long-term impacts of prescribed burning on regional extent and incidence of wildfires—Evidence from 50 years of active fire management in SW Australian forests *For. Ecol. Manage.* **259** 132–42

Bowman D M *et al* 2011 The human dimension of fire regimes on Earth *J. Biogeogr.* **38** 2223–36

Bradstock R A, Hammill K A, Collins L and Price O F 2010 Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia *Landsc Ecol.* **25** 607–19

Bradstock R A *et al* 2012a Modelling the potential for prescribed burning to mitigate emissions from fire-prone, Australian ecosystems *Int. J. Wildland Fire* **21** 629–39

Bradstock R A, Cary G J, Davies I, Lindenmayer D B, Price O F and Williams R J 2012b Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: insights from landscape-scale simulation *J. Environ. Manag.* **105** 66–75

Brook R D *et al* 2004 Air pollution and cardiovascular disease: a statement for healthcare professionals from the Expert Panel on Population and Prevention Science of the American Heart Association *Circulation.* **109** 2655–71

Cope M E *et al* 2004 The Australian air quality forecasting system. Part I: Project description and early outcomes *J. Appl. Meteorol.* **43** 649–62

Cruz M G, Sullivan A L, Gould J S, Sims N C, Bannister A J, Hollis J J and Hurley R J 2012 Anatomy of a catastrophic wildfire: the Black Saturday Kilmore East fire in Victoria, Australia *Forest Ecology and Management* **284** 269–85

Cubison M J *et al* 2011 Effects of aging on organic aerosol from open biomass burning smoke in aircraft and laboratory studies *Atmos. Chem. Phys.* **11** 12049–64

Danielsen P H *et al* 2011 Oxidative stress, DNA damage, and inflammation induced by ambient air and wood smoke particulate matter in human A549 and THP-1 cell lines *Chem. Res. Toxicology* **24** 168–84

Demling R H 2008 Smoke inhalation lung injury: an update *Eplasty* **8** e27

Dether D and Black A 2006 Learning from escaped prescribed fires —lessons for high reliability *Fire Manag. Today* **66** 50–6

Dix-Cooper L, Johnston F, Hasselback P and Rideout K 2014 Evidence Review: Reducing time outdoors during wildfire smoke events: Advice to stay indoors, advice to reduce outdoor physical activity and cancelling *BC Centre for Disease Control, Vancouver BC*

Dowdy A J, Mills G A, Finkele K and de Groot W 2010 Index sensitivity analysis applied to the Canadian forest fire weather index and the McArthur forest fire danger index *Meteorol. Appl.* **17** 298–312

Einfeld W, Ward D E and Hardy C 1991 Effects of fire behavior on prescribed fire smoke characteristics: A case study p 412-419 ed J S Levine *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications* (Cambridge, MA: MIT Press) pp 412–9

Eze I C, Hemkens L G, Bucher H C, Hoffmann B, Schindler C, Künzli N, Schikowski T and Probst-Hensch N M 2015 Association between ambient air pollution and diabetes mellitus in Europe and North America: systematic review and meta-analysis *Environ. Health Perspect* **123** 381

Faustini A *et al* 2015 Short-term effects of particulate matter on mortality during forest fires in Southern Europe: results of the MED-PARTICLES Project *Occupational Environ. Med.* **72** 323–9

Ferguson S A 2001 Smoke management meteorology *Smoke Management Guide for Prescribed and Wildland fire: 2001 Edition* ed C C Hardy (USA: National Wildfire Coordination Group, Boise, ID)

Fernandes P M and Botelho H S 2003 A review of prescribed burning effectiveness in fire hazard reduction *Int. J.Wildland Fire* **12** 117–28

Field R D *et al* 2015 Development of a global fire weather database *Nat. Hazards Earth Syst. Sci.* **15** 1407–23

Fromm M, Tupper A, Rosenfeld D, Servranckx R and McRae R 2006 Violent pyro-convective storm devastates Australia's capital and pollutes the stratosphere *Geophys. Res. Lett.* **33** L05815

Goodrick S L, Achtemeier G L, Larkin N K, Liu Y and Strand T M 2013 Modelling smoke transport from wildland fires: a review *Int. J. Wildl. Fire* **22** 83

Haikerwal A, Reisen F, Sim M R, Abramson M J, Meyer C P, Johnston F H and Dennekamp M 2015a Impact of smoke from prescribed burning: Is it a public health concern? *J. Air Waste Manage. Assoc.* **65** 592–8

Haikerwal A, Akram M, Del Monaco A, Smith K, Sim M R, Meyer M, Tonkin A M, Abramson M J and Dennekamp M 2015b Impact of fine particulate matter (PM2. 5) exposure during wildfires on cardiovascular health outcomes *J. Am. Heart Assoc.* **4** e001653

Hanigan I C, Johnston F H, Henderson S B, Morgan G G, Portner T, Williamson G J and Salimi F 2016 *The Validated Bushfire Smoke Events Database* Australian National University Data Commons (https://gislibrary-extreme-weather.anu.edu.au/biomass_smoke_events)

Hanigan I C, Johnston F H and Morgan G G 2008 Vegetation fire smoke, indigenous status and cardio-respiratory hospital admissions in Darwin, Australia, 1996-2005 *BMC Environmental Health* **7** 42

Henderson S B, Brauer M, MacNab Y C and Kennedy S M 2011 Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort *Environ. Health Perspect.* **119** 1266–71

Henderson S B and Johnston F H 2012 Measures of forest fire smoke exposure and their associations with respiratory health outcomes *Curr. Opin. Allergy Clin. Immunol.* **12** 221–7

Heilman W E, Liu Y, Urbanski S, Kovalev V and Mickler R 2014 Wildland fire emissions, carbon, and climate: Plume rise, atmospheric transport, and chemistry processes *For. Ecol. Manage.* **317** 70–9

Hobbs P V, Reid J S, Herring J A, Nance J D and Weiss R E 1996 Particle and trace-gas measurements in the smoke from prescribed burns of forest products in the Pacific Northwest *Biomass Burning and Global Change* ed J S Levine (Cambridge, Mass: MIT Press) 1996, pp 697–715

Holstius D M, Reid C E, Jesdale B M and Morello-Frosch R 2012 Birth weight following pregnancy during the 2003 Southern California Wildfires *Environ. Health Perspectives* **120** 1340–5

Jain A K, Tao Z, Yang X and Gillespie C 2006 Estimates of global biomass burning emissions for reactive greenhouse gases (CO, NMHCs, and NOx) and CO_2 *J. Geophys. Res.: Atmos.* **111** D06304

Janhäll S, Andreae M and Pöschl U 2010 Biomass burning aerosol emissions from vegetation fires: particle number and mass emission factors and size distributions *Atmos. Chem. Phys.* **10** 1427–39

Jayachandran S 2009 Air quality and early-life mortality during Indonesia's Massive Wildfires in 1997 *J. Human Res.* **44** 916–54

Johnston F H, Webby R J, Pilotto L, Bailie R, Parry D and Halpin S 2006 Vegetation fires, particulate air pollution and asthma: a panel study in the Australian monsoon tropics *International Journal of Environmental Health Research* **16** 391–404

Johnston F H, Bailie R, Pilotto L and Hanigan I 2007 Ambient biomass smoke and cardio-respiratory hospital admissions *BMC Public Health* **7** 240

Johnston F H, Williamson G J and Bowman D M J S 2010 A review of approaches to monitoring smoke from vegetation fires for public health *Air Quality Clim. Change* **44** 17–20

Johnston F H, Hanigan I C, Henderson S B, Morgan G G, Portner T and Williamson G J 2011a Creating an integrated historical record of extreme bushfire smoke events in Australian cities from 1994 to 2007 *J. Air Waste Manag. Assoc.* **2011** 61

Johnston F H, Hanigan I C, Henderson S B, Morgan G G and Bowman D M J S 2011b Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994-2007 *Environ. Res.* **111** 811–6

Johnston F H, Henderson S B, Chen Y, Randerson J T, Marlier M, DeFries R S, Kinney P, Bowman D M J S and Brauer M 2012 Estimated global mortality attributable to smoke from landscape fires *Environ Health Perspect* **120** 659–701

Johnston F and Bowman D M J S 2014 Bushfire smoke: an exemplar of coupled human and natural systems *Geograph. Res.* **52** 45–54

Johnston F H, Purdie S, Jalaludin B, Martin K L, Henderson S B and Morgan G G 2014 Air pollution events from forest fires and emergency department attendances in Sydney, Australia 1996–2007: a case-crossover analysis *Environ. Health.* **13** 105

Jolly W M, Cochrane M A, Freeborn P H, Holden Z A, Brown T J, Williamson G J and Bowman D M J S 2015 Climate-induced variations in global wildfire danger from 1979 to 2013 *Nat. Commun.* **6** 7537

Kaskaoutis D G, Kumar S, Sharma D, Singh R P, Kharol S K, Sharma M, Singh A K, Singh S, Singh A and Singh D 2014 Effects of crop residue burning on aerosol properties, plume characteristics, and long-range transport over northern India *Journal of Geophysical Research: Atmospheres* **119** 5424–44

Keeley J E 2009 Fire intensity, fire severity and burn severity: a brief review and suggested usage *International Journal of Wildland Fire* **18** 116–26

Krstic N and Henderson S B 2015 Use of MODIS data to assess atmospheric aerosol before, during, and after community evacuations related to wildfire smoke *Remote Sens. Environ.* **166** 1–7

Langmann B, Duncan B, Textor C, Trentmann J and van der Werf G R 2009 Vegetation fire emissions and their impact on air pollution and climate *Atmos. Environ.* **43** 107–16

Lavdas L G 1986 An atmospheric dispersion index for prescribed burning *USDA Forest Service, Southeastern Forest Experiment Station* Research paper SE-256 (Macon, GA, USA)

Levy J I, Diez D, Dou Y, Barr C D and Dominici F 2012 A metaanalysis and multisite time series analysis of the differential toxicity of major fine particulate matter constituents *Am. J. Epidemiol.* **175** 1091–9

Lim S S *et al* 2013 A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010 *The Lancet* **380** 2224–60

Loehle C 2004 Applying landscape principles to fire hazard reduction *For Ecol. Manag.* **198** 261–7

Martin K L, Hanigan I C, Morgan G G, Henderson S B and Johnston F H 2013 Air pollution from bushfires and their association with hospital admissions in Sydney, Newcastle and Wollongong, Australia 1994–2007 *Australian and New Zealand Journal of Public Health* **37** 238–43

Meyn A, White P S, Buhk C and Jentsch A 2007 Environmental drivers of large, infrequent wildfires: the emerging conceptual model *Progr. Phys. Geogr.* **31** 287–312

McRae R H D, Sharples J J and Fromm M 2015 Linking local wildfire dynamics to pyroCb development *Nat. Hazards Earth Syst. Sci.* **15** 417–28

National Asthma Council Australia 2015 *Australian Asthma Handbook, Version 1.1* (Australia, Melbourne: National Asthma Council) (http://asthmahandbook.org.au)
Peterson D, Hyer E and Wang J 2014 Quantifying the potential for high-altitude smoke injection in the North American boreal forest using the standard MODIS fire products and subpixel-based methods *J. Geophys. Res.: Atmos.* **119** 3401–19
Pope C A and Dockery D W 2006 Critical Review. Health effects of fine particulate air pollution: Lines that connect *J. Air Waste Manag. Assoc.* **56** 709–42
Pope C A, Brook R D, Burnett R T and Dockery D W 2011 How is cardiovascular disease mortality risk affected by duration and intensity of fine particulate matter exposure? An integration of the epidemiologic evidence *Air Quality, Atmosphere & Health* **4** 5–14
Price O F and Bradstock R A 2011 Quantifying the influence of fuel age and weather on the annual extent of unplanned fires in the Sydney region of Australia *Int. J. Wildland Fire* **20** 142–51
Price O F and Bradstock R 2012 The efficacy of fuel treatment in mitigating property loss during wildfires: insights from analysis of the severity of the catastrophic fires in 2009 in Victoria, Australia *J. Environ. Manag.* **113** 146–57
Price O F, Bradstock R A, Keeley J E and Syphard A D 2012a The impact of antecedent fire area on burned area in southern California coastal ecosystems *J. Environ. Manag.* **113** 301–7
Price O F, Russell-Smith J and Watt F 2012b The influence of prescribed fire on the extent of unplanned fire in savanna landscapes of western Arnhem Land, Australia *Int. J. Wildland Fire* **21** 297–305
Price O F, Penman T D, Bradstock R A, Boer M and Clarke H 2015 Fire leverage in southeast Australia: the biogeography of prescribed fire effectiveness *J Biogeogr.* **42** 2234–45
Price O F, Horsey B and Jiang N 2016 Local and regional smoke impacts from prescribed fires *Nat. Hazards Earth Syst. Sci. Discussion* **16** 2247
Rappold A G, Cascio W E, Kilaru V J, Stone S L, Neas L M, Devlin R B and Diaz-Sanchez D 2012 Cardio-respiratory outcomes associated with exposure to wildfire smoke are modified by measures of community health *Environ. Health* **11** 1
Raffuse S M, Craig K J, Larkin N K, Strand T T, Sullivan D C, Wheeler N J M and Solomon R 2012 An evaluation of modeled plume injection height with satellite-derived observed plume height *Atmosphere* **3** 103–23
Reid C E, Brauer M, Johnston F H, Jerrett M, Balmes J R and Elliott C T 2016a Critical review of health impacts of wildfire smoke exposure *Environ. Health Persp.* **142** 1334–43
Reid C E, Jerrett M, Tager I B, Petersen M L, Mann J K and Balmes J R 2016b Differential respiratory health effects from the 2008 northern California wildfires: A spatiotemporal approach *Environ. Res.* **150** 227–35
Rein G 2013 Smouldering fires and natural fuels *Fire Phenomena and the Earth System: An Interdisciplinary Guide to Fire Science* ed C M Belcher (New York: Wiley) 15–33
Reisen F, Duran S M, Flannigan M, Elliott C and Rideout K 2015 Wildfire smoke and public health risk *Int. J. Wildland Fire* **24** 1029–44
Rothermel R C 1983 How to predict the spread and intensity of forest and range fires *ntermountain Forest and Range Experiment Station General Technical Report INT-143* USDA Forest Service
Sapkota A, Symons J M, Kleissl J, Wang L, Parlange M B, Ondov J, Breysse P N, Diette G B, Eggleston P A and Buckley T J 2005 Impact of the 2002 Canadian forest fires on particulate matter air quality in Baltimore City *Environ. Sci. Technol.* **39** 24–32
Sbihi H, Nicas M and Rideout K 2014 Evidence Review: Using masks to protect public health during wildfire smoke events *BC Centre for Disease Control, Vancouver BC*
Schweizer D W and Cisneros R 2016 Forest fire policy: change conventional thinking of smoke management to prioritize long-term air quality and public health *Air Qual. Atmos. Health* 1–4
Shaposhnikov D *et al* 2014 Mortality related to air pollution with the Moscow heat wave and wildfire of 2010 *Epidemiology* **25** 359–64
Smith R 2012 *The Investigation of the House Losses in the Margaret River Bushfire 23rd November 2011* (Perth, Australia: Envirnment Protection Branch: Western Australian Government)
Sneeuwjagt R J, Kline T S and Stephens S L 2013 Opportunities for improved fire ese and management in California: Lessons from Westen Australia *Fire Ecology* **9**
Sullivan A L and Ball R 2012 Thermal decomposition and combustion chemistry of cellulosic biomass *Atmos. Environ.* **47** 133–41
Surawski N C, Sullivan A L, Meyer C P, Roxburgh S H and Polglase P J 2015 Greenhouse gas emissions from laboratory-scale fires in wildland fuels depend on fire spread mode and phase of combustion *Atmos. Chem. Phys.* **15** 5259–73
Tolhurst K G and McCarthy G 2016 Effect of prescribed burning on wildfire severity: a landscape-scale case study from the 2003 fires in Victoria *Aust For.* **79** 1–14
Trentmann J, Luderer G, Winterrath T, Fromm M D, Servranckx R, Textor C, Herzog M, Graf H-F and Andreae M O 2006 Modeling of biomass smoke injection into the lower stratosphere by a large forest fire: I. Reference simulation *Atmos. Chem. Phys.* **6** 5247–60
Val Martin M, Logan J A, Kahn R A, Ichoku C M, Freitas S R and Cantin A 2009 A parameterization of wildfire emission injection heights in North America: analysis from satellite observations and models *Am. Geophys. Union Fall Meeting Abstracts* vol 1
van Donkelaar A, Martin R V, Spurr R J and Burnett R T 2015 High-resolution satellite-derived PM2. 5 from optimal estimation and geographically weighted regression over North America *Environ. Sci. Technol.* **49** 10482–91
Vilen T and Fernandes P M 2011 Forest fires in Mediterranean countries: CO(2) emissions and mitigation possibilities through prescribed burning *Environ. Manag.* **48** 558–67
Wagner C V 1977 Conditions for the start and spread of crown fire *Can. J. Forest Res.* **7** 23–34
Ward D E, Hao W M, Susott R A, Babbitt R E, Shea R W, Kauffman J B and Justice C O 1996 Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems *J. Geophys. Res.* **101** 23569
Weise D R and Wright C S 2014 Wildland fire emissions, carbon and climate: Characterizing wildland fuels *For. Ecol. Manage.* **317** 26–40
Westphal D L and Toon O B 1991 Simulations of microphysical, radiative, and dynamical processes in a continental-scale forest fire smoke plume *J. Geophys. Res.* **96** 22379
Williamson G J, Price O F, Henderson S B and Bowman D M J S 2013 Satellite-based comparison of fire intensity and smoke plumes from prescribed fires and wildfires in south-eastern Australia *Int. J. Wildl. Fire* **22** 121
Yao J and Henderson S B 2014 An empirical model to estimate daily forest fire smoke exposure over a large geographic area using air quality, meteorological, and remote sensing data *J. Expo. Sci. Environ. Epidemiol.* **24** 328–35
Yuchi W, Yao J, McLean K E, Stull R, Pavlovic R and Henderson S B 2016 Blending modeled forest fire smoke with measured PM2.5 concentrations can improve population exposure assessment for epidemiology and public health surveillance *Atmos. Environ.* **145** 308–17