PHILOSOPHICAL TRANSACTIONS B

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Review

Cite this article: Johnston FH, Melody S, Bowman DMJS. 2016 The pyrohealth transition: how combustion emissions have shaped health through human history. *Phil. Trans. R. Soc. B* **371**: 20150173. http://dx.doi.org/10.1098/rstb.2015.0173

Accepted: 9 February 2016

One contribution of 24 to a discussion meeting issue 'The interaction of fire and mankind'.

Subject Areas:
health and disease and epidemiology, ecology

Keywords:
landscape fire, air pollution, epidemiological transition, mortality, biomass smoke, particulate matter

Author for correspondence:
Fay H. Johnston
e-mail: fay.johnston@utas.edu.au

The pyrohealth transition: how combustion emissions have shaped health through human history

Fay H. Johnston[1], Shannon Melody[1] and David M. J. S. Bowman[2]

[1]Menzies Institute for Medical Research, University of Tasmania, Private Bag 23, Hobart, Tasmania 7001, Australia
[2]School of Biological Sciences, University of Tasmania, Private Bag 55, Hobart, Tasmania 7001, Australia

DMJSB, 0000-0001-8075-124X

Air pollution from landscape fires, domestic fires and fossil fuel combustion is recognized as the single most important global environmental risk factor for human mortality and is associated with a global burden of disease almost as large as that of tobacco smoking. The shift from a reliance on biomass to fossil fuels for powering economies, broadly described as the pyric transition, frames key patterns in human fire usage and landscape fire activity. These have produced distinct patters of human exposure to air pollution associated with the Agricultural and Industrial Revolutions and post-industrial the Earth global system-wide changes increasingly known as the Anthropocene. Changes in patterns of human fertility, mortality and morbidity associated with economic development have been previously described in terms of demographic, epidemiological and nutrition transitions, yet these frameworks have not explicitly considered the direct consequences of combustion emissions for human health. To address this gap, we propose a pyrohealth transition and use data from the Global Burden of Disease (GBD) collaboration to compare direct mortality impacts of emissions from landscape fires, domestic fires, fossil fuel combustion and the global epidemic of tobacco smoking. Improving human health and reducing the environmental impacts on the Earth system will require a considerable reduction in biomass and fossil fuel combustion.

This article is part of the themed issue 'The interaction of fire and mankind'.

1. Introduction

The Earth has supported free-burning fires since there was sufficient vegetation to produce fuel and sufficient oxygen to enable the chemical reactions to take place [1,2]. The subsequent evolution of hominins, the only know life form that can start fires, has shaped the global patterns of fire [3–5]. Fire has been described as a 'near-universal catalyst for most of our exchanges with the world around us, from technology to land use' [6]. It has shaped human physiologies and societies, including settlement patterns, food production, technology, mining, transport and communications. It has been hypothesized that fire enabled humans to develop large brains and hence sophisticated cultures because of the increased nutritional benefits derived from cooked food [7]. The shift from biomass to fossil fuels to power economies is often used to define the start of the Industrial Revolution, and was termed the 'pyric transition' by Pyne [8]. Fire activity on the Earth can be conceptualized in terms of four key phases comprising: (i) natural fire regimes that preceded hominin evolution; (ii) hunter–gatherer fire regimes; (iii) agricultural fire regimes; and (iv) industrial fire regimes [6]. It is important to note that this model does not promote a developmental ladder of cultural 'evolution'; rather it acknowledges that all phases, apart from the pre-hominin, currently coexist on the Earth [4].

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The effects of changed socio-economic patterns inherent in the pyric transition have been described from the perspectives of demographic, epidemiological and nutrition transitions [9–14]. The 'demographic transition' describes population shifts from high fertility and mortality rates, to low fertility and mortality rates in association with transformation from a traditional pre-industrial state to a developed, modernized structure [12,15,16]. The 'epidemiological transition', first proposed by Omran in 1971 [11], further characterizes the mortality changes outlined by the demographic transition. It proposes that historical transitions in life expectancy are underscored by systematic shifts in disease patterns in which chronic and degenerative disease come to dominate, while the role of infection as the primary cause of death diminishes. These are generally described as functions of 'modernization', encompassing technological advances and industrialization, reduced crowding and improvement in overall living standards and healthcare [11,17]. The 'nutrition transition' can be conceptualized as a contributor to the epidemiological transition. It describes major shifts in human diet and activity patterns associated with modernization, urbanization and globalization. Intake of calorie-dense and nutritionally devoid food, accompanied by an increasingly sedentary lifestyle gives rise to degenerative and non-communicable diseases such as diabetes, heart disease and cancer, which stabilize as medical interventions and public health adaptations are implemented. All these frameworks share similar socio-economic, cultural and technological determinants [9,18].

The health and demographic transitional frameworks described above have been variously criticized for ambiguity in describing timescales and underlying determinants of the observed population dynamics [19], for their more limited relevance to societies outside highincome regions of the world [20], and for their inability to address the complexity of the underlying determinants of cause-specific mortality [17]. Yet despite these recognized limitations, the overall concept of health transitions remains helpful and has gained more currency and utility with the advent of the Global Burden of Disease (GBD) collaboration studies, originally commissioned by the World Bank during the 1990s. The GBD framework is a major international collaborative programme of quantifying and comparing the major causes of global mortality, reduced life expectancy and, more recently, disability, to the level of individual countries and is now funded by the Bill & Melinda Gates Foundation [21]. This initiative has allowed global health indicators to be objectively quantified using consistent methods to display trends over time, by location, or by the socio-demographic characteristics of different populations. The programme has formed the basis for advocating for action for a new health transition—a vision for global health improvement driven by a coordinated response to support development of accessible health services and responses to threats associated with global challenges such as environmental change [14,22].

Often overlooked in these constructs are the public health consequences of air pollution that have literally fuelled domestic life, powered the Industrial Revolution and driven climate change through greenhouse gas pollution [23,24]. Here we propose a 'pyrohealth transition' that describes the health impacts associated with human practices of biomass and fossil fuel combustion spanning hunter–gatherer to industrial economies, including the global epidemic of tobacco smoking. We (i) briefly outline the health effects of air pollution, including biomass and fossil fuel smoke, at the individual and population scales; (ii) outline key phases in the pyrohealth transition; (iii) consider the health impacts of the patterns of pollution that emerge from the emissions associated with the various phases of the pyrohealth transition: landscape biomass burning, household air pollution, industrial air pollution, and tobacco and other forms of smoking; and (iv) use the framework of the GBD to contextualize direct, smoke-related mortality impacts. This presents a holistic view of the human health—combustion nexus on the Earth today, while acknowledging that smoke has numerous indirect effects on the Earth system and human health that are beyond the scope of this review [25].

2. Health impacts of smoke

Air pollution is now recognized as the single most important global environmental risk factor for human mortality [26]. There are numerous different kinds of pollutants in emissions from biomass and fossil fuel combustion, including both gases and suspended particles that are largely made up of elemental and organic carbon compounds. Despite the complex toxic profile of smoke chemistry, adverse health impacts from smoke have been best characterized for suspended particulate matter (PM). PM smaller than 2.5 μm in diameter ($PM_{2.5}$) is regarded as more important for human health than larger-sized particles, although larger-sized fractions have also been associated with health impacts. The dominant source of $PM_{2.5}$ at the global scale is combustion, the focus of this paper, although other sources include aerosolized sea salt, aeolian dust or fertilizers [27–29]. The impact of particulate air pollution relates to its ubiquitous nature rather than high toxicity. Thus, health impacts are generally small at an individual level, but when entire populations are exposed the public health impacts can be considerable. Clinical manifestations depend upon individual exposure patterns and underlying individual susceptibility. Through biological mechanisms, such as increased oxidative stress and heightened inflammatory responses, the development and progression of cardiovascular, respiratory and other diseases are promoted [30,31]. However, many factors influence these pathways, and serious health outcomes, such as mortality, generally only become measurable if very large numbers of people are studied [32]. At the global scale, the mortality from air pollution is not driven by the exacerbation of lung diseases as many might assume, but by increases in short- and long-term cardiovascular mortality [26]. However, at longer timescales it is also an important contributor to population rates of lung cancer [33].

Combustion in specially designed engines and furnaces has lower emission of particles than when the fuels are burnt in open fires that have less-complete combustion. Incomplete combustion produces a suite of compounds in addition to PM, including carbon monoxide, oxides of nitrogen, inorganic acids, aldehydes, polycyclic aromatic hydrocarbons and trace elements, many of which are toxic in their own right [34]. The specific constituents of emissions will vary according to type (flaming or smouldering) and rate of combustion, which in turn are influenced by fuel moisture, available oxygen, temperature and dynamic chemical processes in the smoke plume [35].

The evidence base concerning the health impacts of these smoke mixtures, in which concentrations of $PM_{2.5}$ are measured as a marker of the overall mix, has grown considerably in the last decade. These findings are generally consistent with the vast literature on background urban PM that has fewer co-pollutants than a smoke plume. The health impacts of ambient biomass smoke pollution also have some parallels with tobacco smoking, and with household air pollution from cooking fires, noting the vast differences in personal exposure in each case. Active and passive exposure to tobacco smoke is associated with numerous health conditions including cardiovascular diseases, respiratory diseases including infections, asthma and chronic obstructive pulmonary disease and cancer, impaired immune function, intrauterine growth restriction, sudden infant death syndrome, reproductive health disorders and diabetes [36,37]. In the context of indoor settings where household fires produce severe long-term exposure to air pollution, clear associations with severe respiratory infections, chronic lung disease and lung cancer have been identified [38]. Similarly, exposure to indoor smoke from other sources such as burning incense has been associated with respiratory symptoms, immune dysfunction and malignancy [39–47].

Exposure to outdoor smoke from landscape fires is strongly associated with increasing respiratory symptoms, worsening of existing respiratory diseases, and hospital admissions and deaths from respiratory causes [48]. In direct comparisons between equivalent concentrations of PM from background urban sources and PM from landscape fire smoke, stronger inflammatory responses and larger-sized association with adverse respiratory impacts have been described for smoke-derived PM [49,50]. There are fewer studies of the impacts on population mortality rates; however, the available evidence suggests that impacts are very similar to those associated with $PM_{2.5}$ from background urban sources for short-term mortality but studies of the association with long-term mortality rates are lacking [31,51,52]. The evidence base about the impact on cardiovascular diseases is small but growing and associations with outcomes such as cardiac arrest and heart failure are emerging [53].

3. Pyrohealth transition

The human use of fire at the global scale can be mapped to the major pyric phases described above: (i) hunter–gatherer fire regimes; (ii) agricultural fire regimes; and (iii) industrial fire regimes. These broadly correspond to the phases described by the demographic, epidemiological and nutrition transitions outlined above.

The pyrohealth transitions have different mixes of exposure to combustion emissions that can be considered from four major contributing sources, each with particular spectra of human exposure and health impacts (table 1). These are: (i) the burning of landscapes for a variety of purposes that can range from traditional indigenous uses such as hunting, burning of agricultural residue, clearing rainforest to convert land to other purposes, or the management of biomass fuels in fire prone environments; (ii) domestic combustion of biomass or other solid fuels for purposes such as heating and cooking; (iii) fossil fuel combustion at industrial scales for electricity production, transport and other mechanized activities; and (iv) personal and environmental exposure to tobacco smoke and other forms of smoking for personal or religious purposes. It is important to note that while these four components of the pyrohealth transition vary in their geographical scale and level of economic importance, they are not sequential or mutually exclusive. All, other than the industrial-scale combustion of fossil fuels, have been a feature of human societies throughout history to the present day (figure 1).

For example, the management of landscapes through deliberate fire management is a feature of all pre-industrial, agricultural and industrial societies; however, the regimes that emerged from these practices vary geographically and historically. Similarly, the use of fire at a household level for heating or cooking occurs to a varying degree in every economy. The extent of air pollution from fossil fuel combustion shows distinct trends and spatial patterns associated with the scale and technological sophistication of industrialization. The inhalation of smoke for physiological and psychotropic effects from various plants is a long standing traditional practice. However, the introduction of tobacco to Europe in the 16th century and global uptake following mechanization and industrialization completely changed the magnitude of exposure and health impacts.

(a) Landscape fires

Human societies have a long history of the use of fire at the landscape scale for many purposes often creating fine-scaled mosaics [54]. While no studies on smoke exposure from traditional indigenous landscape burning exist, the smaller mosaic of patch burning promotes small low-intensity fires [55,56], which overall produce relatively lower emissions, due to the smaller spatial size and lower fuel loads under such fire regimes [54]. The cessation of indigenous burning, active fire suppression, introduced species, and a warming climate are all contributing to increasingly frequent, large-scale, intense fires in many flammable landscapes [6,54,57]. Emissions from large landscape fires can be transported for long distances affecting large and small population centres far from the fires themselves [58]. Smoke episodes from severe landscape fires result in measureable increases in individual symptoms and in population indices of ambulance call outs, admissions to hospital and mortality [52]. Fire suppression might also have other human health impacts in addition to the accumulation of fuels and promotion of more severe fires. For example, it has been suggested that fire suppression alters the risk and transmission of infectious-disease pathogens and host–parasite dynamics [59].

The changes to landscape fire activity and associated health impacts are well illustrated by northern Australian savannas. Aboriginal Australians have a long tradition of burning tropical savannas to create wildlife habitat and ‘humanize’ the landscape [54–56,60,61]. The transfer from Aboriginal to European types of savanna burning that occurred from 1950s onwards has been shown to be associated with larger and more frequent fires resulting in increased population exposure to fire smoke pollution in the Northern Territory capital city, Darwin [62]. Traditional Aboriginal burning practice has also been shown to benefit the health of Aboriginal people by providing physical activity, and facilitating access to nutritious foods, traditional

Table 1. Pyrohealth transitions in the context of the pyric phases, demographic, nutrition and epidemiological transitions. Adapted from Popkin [18].

economy	hunter–gatherer	agricultural	pre-industrialization	post-industrial
residency patterns	rural, low density	rural, a few small, crowded cities	chiefly rural, urbanization increases, megacities develop	dispersal of urban population, rejuvenation of lower-density cities, increase in urbanisation of rural areas encircling cities
predominant type of fire	landscape/domestic	landscape/domestic	landscape/domestic/industrial/tobacco smoking	landscape/domestic/industrial/tobacco smoking
fuel type	biomass	biomass	biomass and fossil fuels	biomass and fossil fuels
predominant human uses of fire	heating, cooking and lighting hunting, land management	heating, cooking and lighting farming and agriculture, fire and forest management	heating, cooking and lighting land clearing, farming and agriculture widespread tobacco smoking tobacco smoking epidemic emerging	technology, manufacturing, mining and industry, transport, communication, production, advances in healthcare/antibiotics tobacco smoking epidemic diminishing wildfire management and land clearing
fire-related drivers of human health impacts	outdoor air pollution highly variable in concentration and duration and population level exposure chronic severe indoor air pollution *positive impacts* traditional landscape burning is often associated with increased physical activity and access to nutritious wild foods; however, food supply might not be consistent	agricultural and deforestation burning can produce prolonged and severe pollution episodes chronic severe indoor air pollution—greater risk of exposure to toxic compounds in indoor settings such as carbon monoxide especially if no system to remove emissions *positive impacts* food security using fire in traditional agricultural settings associated with high physical activity	severe outdoor air pollution from domestic and industrial sources severe outdoor pollution from deforestation fires chronic severe indoor air pollution—greater risk of exposure to toxic compounds in indoor settings, such as carbon monoxide, especially if no system to remove emissions	outdoor air pollution, improvements from industrial and transport sectors outdoor pollution form severe landscape fires emerging indoor pollution from domestic fires receding climate forcing and global environmental change reduced physical activity and increased consumption of energy-dense foods changes in the micro-biome *positive impacts* access to healthcare food security, although increasing risk with climate change
population demographic profile	low fertility, high mortality, low life expectancy young population	high fertility, high mortality, low life expectancy young population	fertility static, then declines; mortality declines slowly, then rapidly; population growth chiefly young but ageing population	ageing population

(*Continued*.)

Table 1. (*Continued.*)

economy	hunter–gatherer	agricultural	pre-industrialization	post-industrial
characteristics of population health impacts	injuries, infectious diseases (no epidemics) respiratory infections exacerbated by indoor smoke	injuries, nutritional deficiencies (depending on food security), infectious-disease endemics and epidemics respiratory infections exacerbated by indoor smoke	infectious diseases depending on underlying environmental conditions (crowding/sanitation) and health status; nutritional deficiencies recede chronic diseases emerge, especially cardiovascular disease, acute and chronic respiratory diseases, and cancer	infectious diseases recede due to improved environmental conditions and medical advances, chronic disease related to sedentary lifestyle and pollution predominate food and water insecurity, political insecurity and natural disasters, physical injuries and population displacement emerge secondary to climate change
scale of fire-related environmental health risk	individual and family/household groups	individual, household and community	individual, household and community	individual, community and global

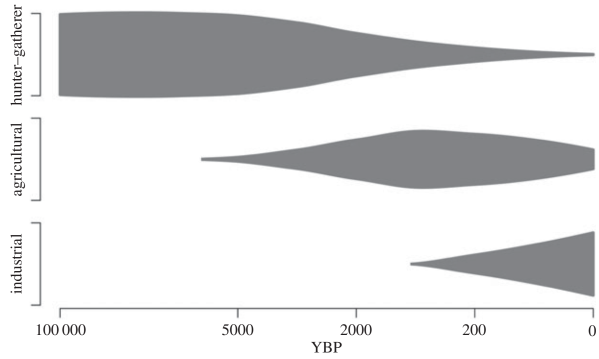

Figure 1. A schematic of dominant human economies through time. While landscape fires, domestic fires and smoking have been a part of human societies throughout history, industrialization has dramatically increased human exposure to outdoor air pollution and tobacco smoke (table 1).

lands and cultural practices [63]. Rekindling these practices might have landscape-wide biodiversity benefits and reduce regional smoke pollution [61,64].

Fires to remove crop residues remain a common and important source of air pollution in many parts of the world with well-documented adverse health impacts [65–67]. However, the most extreme and prolonged landscape fire smoke events are now caused by tropical deforestation and peat fires that are used to clear land for agricultural purposes [68]. Smoke from tropical deforestation fires is one of the most important and potentially modifiable drivers of global estimates of mortality from landscape fire smoke [69] and climate forcing attributable to landscape fire emissions [70]. Some authors have suggested that human-set fires and agriculture may have started to impact on the Earth system in the Early Holocene or Late Pleistocene [71]. Although forests have been cleared to create agricultural landscapes in the past, particularly the 18th and 19th centuries, resulting in a sharp spike in global carbon emissions, this scale of burning was much lower than the current wave of tropical deforestation fires [72].

(b) Domestic

Fire became a regular technology for many (if not all) hominin populations between 300 000 and 400 000 years ago, and possibly much earlier [73,74]. However, it remains unclear whether this had any health impacts or influenced human evolution [75]. Health impacts attributed to exposure to domestic-fire smoke have been observed as soot deposits in the lungs of Egyptian mummies more than 3000 years old [76] and in the bony changes of skeletons from different stages of history. For example, a study of the sinus cavities of ancient human skulls identified a peak prevalence of sinusitis during medieval times, attributed to the use of indoor fires and associated smoke exposure [77]. Biomass fuels have been well documented from ancient China to the present [78] and indoor fires remain the dominant source of cooking fuel for approximately 40% of the world's population today [38]. This source of combustion is associated with many adverse health outcomes, including pneumonia, tuberculosis, chronic obstructive pulmonary disease, asthma, lung cancer, low birth weight, cataracts and cardiovascular events [79]. At the global scale, household air pollution is currently estimated to be responsible for the greatest number of annual deaths from air pollution [27]. Another regionally important source of indoor air pollution is the burning of incense, which is an important daily

Table 2. Estimated annual global and Southeast Asian mortality from air pollution related to landscape fires during El Niño and La Niña conditions, and domestic fires, industrial emissions and tobacco smoking for the year 2000. While the methods used for deriving each estimate varied, this provides a broad indication of the relative importance of each source of air pollution for human health. The estimate for ambient PM encompasses $PM_{2.5}$ from all sources including landscape fires. Data were derived from [69,93].

	smoking (including exposure to second hand smoke)	household air pollution	ambient air pollution ($PM_{2.5}$)	landscape fire smoke La Niña (Sep 1999–Aug 2000)	landscape fire smoke El Niño (Sep 1997–Aug 1998)
global	5 692 000	2 940 000	2 672 000	262 000	532 000
Southeast Asia	485 000	269 000	120 000	43 000	296 000

practice in homes and temples in countries where Buddhism and Taoism are mainstream religions [80]. High concentrations of smoke particles and gases are common, where use is extensive, or in poorly ventilated settings [39,80–84].

(c) Industrial fires

The use of combustion for manufacturing artefacts reaches back to the Palaeolithic, and increased with the smelting of metals that sustained the bronze and iron ages [85]. The health impacts of these industries are unknown but were certainly localized. Air quality impacts of substituting coal for biomass fuels for domestic use and small-scale industries was clearly evident in the British Isles during the 15th century [77]. The impacts on air and possible associations with poor health included elevated mortality rates, which were documented by early members of the Royal Society, including John Evelyn [77]. In 1661, John Evelyn described the health impacts of air pollution in London, writing: '(...) this pestilent smoke (. . .) so fatally seizing on the lungs of the inhabitants, that cough and consumption spare no man' [86]. In London and many other western industrial countries, including the USA, severe pollution episodes became a routine feature of many large cities until well in to the 20th century, and investigations into mortality impacts spawned the modern discipline of air pollution epidemiology [87]. Today, combustion particles are the dominant sources of outdoor air pollution and the major driver of its global mortality impacts, especially in rapidly industrializing and densely populated regions of the world, such as India and China [27]. Particulate air pollution, even at the vastly lower concentrations now present in many cities, is associated with a wide range of health outcomes, including death, with no lower level below which there are no health effects [51].

(d) Inhaling smoke

Numerous human cultures have used fire for ceremonial and social purposes, including the fumigation of dwellings with smoke as a part of religious practices or to self-administer physiological stimulatory and psychotropic compounds [88]. It is likely that smoking is an ancient practice although demonstrating this is not possible with existing archaeological materials. The practice of smoking moved from an intermittent activity constrained by supply and defined social customs, to a global epidemic in the late 19th century. This was driven by the invention of a machine, patented in 1881, which could produce 100 000 cigarettes per day, and subsequent mass-marketing and international trade [89]. This conjunction of industrialization and globalization added another layer to the existing sources of indoor and outdoor combustion emissions already shaping human health and well-being. There was a long lag between the social acceptance of tobacco smoking and the widespread recognition of the substantial health impacts, which were disputed given the considerable revenues for both the tobacco industry and governments. Tobacco smoking is a leading cause of preventable global illness and death [36]. While tobacco control initiatives are central to the health policies of high-income industrialized societies, the vast majority (80%) of the 879 million current tobacco smokers across the world now live in low- and middle-income countries [90,91], where public health control measures are less established. By contrast, the prevalence of tobacco smoking continues to decline in Northern and Western Europe, North America and the Western Pacific region, with many countries aiming to achieve a tobacco 'endgame' [92]. This changing pattern of the global tobacco epidemic is expected to result in a shift of tobacco-related disease burden from the developed world to low- and middle-income countries over the next two decades, with 70% of future tobacco-related deaths expected to occur in low-income countries [92].

4. Comparative global mortality impacts

Global health impacts of air pollution, especially PM, have been evaluated under the broad headings of landscape fire smoke, household air pollution, outdoor air pollution, and tobacco smoke by the GBD collaboration or by teams using broadly comparable approaches [26,27,69]. Data for the GBD collaboration are publicly available online through the Institute for Health Metrics and Evaluation at the University of Washington from 1990 to 2013, allowing comparisons of results through time and by geographic region [93].

Table 2 shows the absolute number of estimated deaths for the entire globe and for the World Health Organization (WHO) region of Southeast Asia for 2000 from the four main sources of combustion emissions, and illustrates the large influence of climate on estimated mortality from landscape fire emissions [69]. Overall in 2000, there were an estimated 5.7 million deaths attributed to smoking tobacco, 2.9 million deaths attributed to household air pollution and a further 2.7 million attributed to ambient $PM_{2.5}$, the majority of which comes from combustion emissions globally, although in some places other sources such as crustal particles and fertilizers make substantial contributions [27]. Together, tobacco smoke, ambient and household air pollution made up 23% of the annual global mortality for 2000 [93]. Figure 2 shows the mortality rates per 100 000 people, allowing a direct comparison of Southeast Asia with global data. Landscape fire smoke is a specific source of ambient air pollution that is especially important in Southeast Asia.

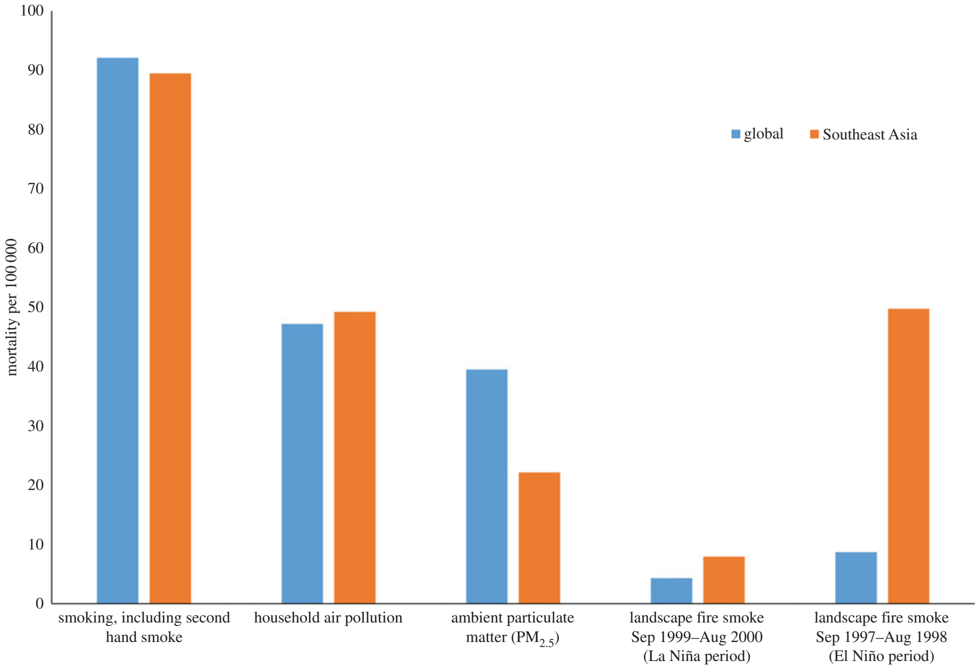

Figure 2. Global (blue—left) and Southeast Asian (orange—right) estimates of mortality rates per 100 000 from smoking, household air pollution and outdoor PM for the year 2000 [93], and the estimate for PM from landscape fire smoke for 1999–2000, a strong La Niña period, and 1996–1997, a strong El Niño period, which coincided with some of the most severe landscape forest and peat fires in Southeast Asia [69]. This demonstrates the general pattern of mortality impacts from different sources of combustion, and shows the regional importance of landscape fires and the strong influence of climatic conditions on health impacts from landscape fires. The estimate for ambient PM includes $PM_{2.5}$ from all sources, including landscape fire smoke, and non-combustion sources; however, combustion sources are estimated to account for the majority of ambient $PM_{2.5}$ globally, and in Southeast Asia landscape fire smoke is the dominant source of ambient $PM_{2.5}$ [27]. Landscape fire smoke mortality estimates were based on deaths from all causes rather than cause-specific mortality used for the estimates for other sources [69]. Smoking-related mortality includes that due to second-hand tobacco smoke, which accounts for about 8% of the total burden.

Comparing the results for strong El Niño and La Niña time periods clearly demonstrates the potential influence of climate on landscape fires and human mortally, and the emerging role of landscape fire on a warming planet.

5. Pyrohealth transitions: a compounding global problem

More than 80% of deaths related to cardiovascular disease worldwide now occur in low- and middle-income countries, with substantial gains for wealthier nations due to reduced smoking rates, better preventive care and sophisticated public health interventions [94]. In many emerging industrializing economies the emergence of such chronic diseases associated with industrialization did not replace the pre-industrial dominance of infectious diseases but simply added to them. This is sometimes termed the 'double burden' of disease and many communities in the Asia Pacific regions exemplify this situation [95]. Similarly, new sources of fire emissions often added to, rather than replaced, the existing burden. For example, in parts of Southeast Asia, landscape fire emissions due to rampant deforestation and peat fires, household, transport and industrial emissions, and smoking rates are all among the highest documented anywhere in the world. This could be conceptualized as a 'quadruple burden' of combustion emissions. In settings already experiencing a double burden of disease related to the epidemiological transitions, this becomes an important interaction (figure 2). Exposure to degraded air quality drives and exacerbates both chronic (especially cardiovascular), and infectious (especially respiratory) diseases, major causes of global mortality and years of life lost, respectively. In high-income regions, including Australia, Europe and North America, the contribution of biomass smoke to the burden of ill health is also becoming increasingly important. Smoke from domestic heating is a major source of outdoor air pollution and in some regions is a modifiable cause of mortality [96]. Smoke exposure from severe landscape fires and smaller planned fires is increasing in frequency and severity, and these forms of exposure are emerging as public health issues in their own right [58,97]. Finally, deforestation fires and fossil fuel combustion are also major drivers of climate change through the emission of greenhouse gases. As illustrated in figure 2, climate patterns have a large impact on mortality from landscape fire smoke [69] and have the potential to drive further global environmental change through the massive emissions of long-stored carbon [98]. Although the health impacts are indirect and considerably delayed, climate change is recognized as 'the biggest global health threat of the 21st century' [99].

6. Conclusion

The use of fire by humans comes with a mix of risks and benefits, some of which are obvious and immediate, and others that are indirect and lagged. The burden of disease caused by fire use has rarely been considered holistically, even though the individual impacts are increasingly well understood, such as those associated with industrial air pollution and tobacco smoking. Here we propose a pyrohealth transition to facilitate holistic thinking about the human health cost of humanity's 'combustion habits'. According to our model, hunter–gather fire use would probably have caused the lowest adverse health effects given the small scale of landscape burning and a predominance of open-air, rather than indoor, cooking fires. The transition to agriculture and permanent settlement would have considerably increased smoke exposure due to indoor cooking. The Industrial Revolution powered by fossil fuels saw a steep change in smoke exposure with dramatic deleterious health outcomes that have gradually been mitigated through technological improvements and regulations in higher-income regions. However, there is also increasing extreme wildfire in flammable landscapes as a consequence of the breakdown of indigenous fire management and policies of total fire suppression that allow the accumulation of forest fuels, resulting in episodic extreme smoke pollution events in urban airsheds. Industrialization has seen a pandemic of tobacco smoking-related diseases, which is being stemmed in the developed world through public health campaigns and legislation. All phases of pyrohealth transition are occurring on the Earth, with the most extreme impacts in lower-income regions of the world, where deforestation fires on the agriculture frontier, reliance on biomass combustion for cooking, rapid industrialization and a high prevalence of tobacco smoking can occur concurrently. Reducing smoke pollution from biomass and fossil fuel combustion is critical for improving human health and reducing the environmental impacts on the Earth system.

7. Meeting discussion

Michael Coughlan (*University of Georgia, USA*). Do you have any thoughts on the conflict between prescribed burning initiatives and air quality concerns and regulations?

F.J. Regulatory responses to air pollution are driven by the desire to protect public health. However air quality guidelines have not historically considered severe wildfires or the deliberate burning of landscapes for fuel management or other reasons. All types of landscape fires affect air quality and the impacts on community health will vary according the number of people affected, and the severity and duration of the smoke exposure. The issue here is the need to balance the public health risks and benefits of deliberate burning, with the potential risks and benefits of not burning. Even the most well accepted, evidenced-based interventions can sometimes have serious side-effects and I would put prescribed burning into this category. This does not mean stopping prescribed burning if the overall trade-offs of risks supports its use. But it does mean that those who burn have a major responsibility to manage and minimize the entirely predictable 'side effect' of adverse health impacts among people exposed to the smoke, even if these impacts are expected to be much lower than those generally associated with wildfires. Achieving the best overall outcomes requires excellent collaboration and communication between health and fire management experts, and members of the communities who are affected by prescribed burns and wildfires.

Authors' contributions. F.H.J. conceived the work and drafted the manuscript, S.M. conducted detailed literature reviews, D.M.J.S.B. contributed to the conceptual framework and synthetic analysis. All authors contributed to writing the manuscript and gave final approval for publication.

Competing interests. We declare we have no competing interests.

Funding. F.H.J. is supported by an Early Career Research Award from the Australian Research Council. S.M. is supported by the Australian Department of Health and Aging. D.M.J.S.B. is supported by the University of Tasmania. F.H.J. and D.M.J.S.B. were supported to attend the discussion meeting by the Royal Society, London.

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