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Concept Paper

Can Air Quality Management Drive Sustainable Fuels Management at the Temperate Wildland–Urban Interface?

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Abstract: Sustainable fire management has eluded all industrial societies. Given the growing number and magnitude of wildfire events, prescribed fire is being increasingly promoted as the key to reducing wildfire risk. However, smoke from prescribed fires can adversely affect public health. We propose that the application of air quality standards can lead to the development and adoption of sustainable fire management approaches that lower the risk of economically and ecologically damaging wildfires while improving air quality and reducing climate-forcing emissions. For example, green fire breaks at the wildland–urban interface (WUI) can resist the spread of wildfires into urban areas. These could be created through mechanical thinning of trees, and then maintained by targeted prescribed fire to create biodiverse and aesthetically pleasing landscapes. The harvested woody debris could be used for pellets and other forms of bioenergy in residential space heating and electricity generation. Collectively, such an approach would reduce the negative health impacts of smoke pollution from wildfires, prescribed fires, and combustion of wood for domestic heating. We illustrate such possibilities by comparing current and potential fire management approaches in the temperate and environmentally similar landscapes of Vancouver Island in British Columbia, Canada and the island state of Tasmania in Australia.

Keywords: fire management; fuels management; wildfire; prescribed fire; mechanical thinning; green fire breaks; smoke; air pollution; public health; air quality regulation

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1. Introduction

Unlike other natural hazards, landscape fires can be both started and suppressed by humans [1] (see Table 1 for our definitions of terms). Globally, Indigenous peoples have inhabited flammable landscapes for thousands of years using naturally ignited and intentionally set fires in subsistence economies that sustained biodiversity [1]. Colonization has disrupted these socio-ecological traditions, and no industrial economy has achieved such sustainable existence with landscape fire [2]. Indeed, fire management is increasingly characterized as being in crisis in many flammable landscapes across the world. This is due to a constellation of factors, including rapid expansion of the wildland–urban interface (WUI), recent wildfires exceeding suppression capabilities, and climate change driving longer and more extreme wildfire seasons [3]. Accordingly, there is increasing recognition of the need for more sustainable management of fuels, particularly at the WUI.

Table 1. Definitions of terms as used in this work, logically organized by broad category.

Category	Term	Definition
Types of Fire and Sources of Smoke	Landscape fire	Any fire burning on the landscape, regardless of its cause
	Prescribed fire	Fire intentionally set and managed on the landscape to reduce wildfire risk, achieve various ecological goals, and sustain or restore biodiversity
	Wildfire	Fire unintentionally burning on the landscape (and sometimes into human settlements), which can have natural or anthropogenic causes
	Slash burning	Burning of debris to regenerate logged forests or cleared land
	Pile burning	Collection of debris from logging and land clearing into piles on the landscape, and subsequent burning of those piles to reduce material and wildfire risk
	Residential wood burning	Use of whole or pelletized harvested wood to provide residential space heating
	Bioenergy	Generation of heat and electricity for domestic and industrial consumption using woody debris (raw or pelletized) from logging, land clearing, and other industries
	Wood pellets	A common fuel type for generation of bioenergy (also known as densified biomass fuels)
Fire, Fuel, and Landscape Management	Fire management	The control of landscape fires through land management and fire suppression techniques
	Fuels management	The reduction of fuels to reduce landscape fire risk and intensity
	Sustainable fire management	Management of fire and fuels such that ecological processes, biodiversity, and human values are maintained
	Wildland-urban interface (WUI)	The landscape interface where native vegetation and urban areas intermingle
	Wildfire risk	Probability that wildfire will occur in any given season, with particular focus on destructive intersection with the WUI
	Fire hazard	The quantity and combustibility of wildland fuels
	Fire weather	A group of meteorological conditions that affect the spread of landscape fire, including air temperature, relative humidity, wind speed, precipitation, and drought
	Fire break	A natural or artificial gap in vegetation or other combustible material that acts to slow or stop the progress of a wildfire
	Green fire break	A natural or planted belt of low-flammability vegetation designed to impede the spread of landscape fires
	Mechanical thinning	Manual and machine-assisted removal of fuels from the landscape
	Woody debris	Waste wood produced by logging, land clearing, and other activities on the landscape
	Biodiversity	Diversity and abundance of lifeforms across all taxonomic ranks and phylogenies
Air Quality	Smoke	A complex type of air pollution comprising particles and gases formed by incomplete combustion of wildland fuels or harvested wood
	Fine particulate matter ($PM_{2.5}$)	Particles less than 2.5 microns in aerodynamic diameter
	Air pollution	The presence or introduction of a harmful substance or substances into the ambient air
	Air quality	The degree to which the ambient air is free of pollution
	Air quality regulation	Statutes and rules designed to improve and protect air quality considering factors such as achievability, environmental impacts, and human health
	Air quality standards	Ambient concentrations of specific air pollutants that are permissible according to air quality regulations
	Air quality management	Activities undertaken by an agency or group of agencies to improve air quality

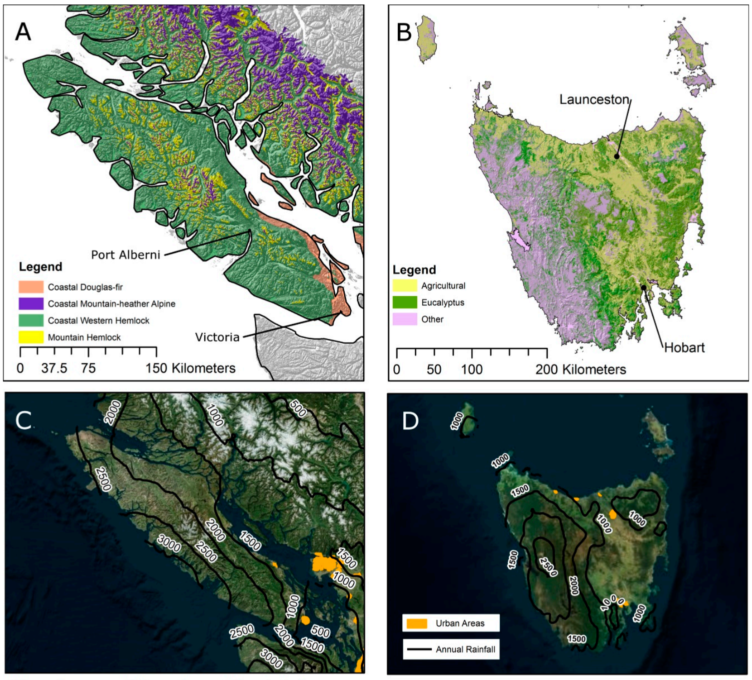
There is growing acceptance among fire managers that prescribed fire, the intentional and managed application of landscape fire, can reduce wildfire risk [4]. Nonetheless, this approach has a number of downsides, including: (1) risk of escaped prescribed fires accidentally destroying the property and infrastructure they were intended to protect. This means that each operation carries the heavy transactional costs of negotiating with multiple land tenures, other stakeholders, and insurance providers [5]; (2) blunted effectiveness of prescribed fire during extreme fire weather, because reduced fuel loads do not limit wildfire spread in hot, dry, and windy conditions [6]; (3) shifting of the timing and/or number of days available for prescribed fire under a changing climate [7–9]; and (4) management of smoke pollution to minimize its public health impacts [10]. Of these drawbacks, the latter is putting increasing constraint on the use of prescribed fire as the adverse effects of smoke on human health become clearer [11–14].

Much like air pollution from other sources, smoke pollution from landscape fires has been associated with increased human morbidity and mortality in exposed populations [11,12]. Indeed, thousands of studies describing the harmful effects of air pollution from multiple sources have driven regulations, policies, and technologies to reduce emissions from vehicles, industry, power generation, and space heating. Such advances have yielded significant health and economic benefits over recent decades because they reduce the immediate harms and the burden of chronic disease associated with ongoing air pollution exposures [15]. Smoke from landscape fires is less amenable to control, but also leads to health risks. Smoke from wildfires is typically excluded from air quality regulations, while smoke from prescribed fires is typically included. Prescribed fires can thus lead to non-compliance with air quality standards [16].

In response to major wildfire disasters there has been a marked increase in the use of prescribed fire surrounding cities in southern Australia, with associated increases in air pollution. The trade-offs between prescribed and wildfire smoke are poorly understood and demand transdisciplinary research that considers human health, fire risk reduction, and biodiversity effects [17,18]. Nonetheless, smoke from prescribed fires can cause serious health harms. For example, Broome et al. (2016) have shown that six days of prescribed fire smoke in the Sydney Basin in May 2016 resulted in 14 deaths and 91 hospital admissions [14].

Policies to manage tensions caused by smoke from prescribed fires are evolving worldwide. In the United States (US), enforcement of the regulatory Clean Air Act requires jurisdictions exceeding the National Ambient Air Quality Standards (NAAQS) to implement air quality management plans that may restrict or prevent the use of prescribed fire [19,20]. As such, some air quality regulators may have the authority to shut down prescribed fires, or to issue large fines. We highlight this legislation because the current approach to air quality in the US is arguably the most rigorous and effective global example. Among fire managers, there is a concern that smoke regulation is hindering effective fuels treatment with prescribed fire [21]. For instance, North et al. (2015) recently suggested that the US Environmental Protection Agency should exempt prescribed fire smoke in the same way that it exempts wildfire smoke, which can be regarded as an unmanageable exceptional event [22]. Here, we present an alternative perspective. Rather than exempting prescribed fires from existing air quality regulations, we argue that adapting and refining those regulations and integrating them with fire management can act to protect human health and to drive improvements in fuels management at the WUI across temperate flammable landscapes.

We present two case studies of fire-prone landscapes in temperate regions working towards these objectives: Vancouver Island, Canada and Tasmania, Australia (Figure 1). Both of these islands are similar with respect to size, climate, and human populations, but they differ with respect to how they manage fuels and wildfire risk. These examples offer a valuable illustration of the diversity in contemporary approaches to fire management and air quality protection. It is important to note at the outset that we are not promoting the Canadian, Australian, or US system of smoke management. Rather, building on these case studies, we are arguing that elements of all three could be strengthened and leveraged to drive sustainable fuels management at the temperate WUI.



Urban Areas and Mean Annual Precipitation

Wildland-Urban Interface

Figure 1. Geographic context of Vancouver Island, Canada (left), and Tasmania, Australia (right). The broad vegetation cover of these temperate forested islands is controlled by elevation (**A**,**B**) and precipitation gradients (**C**,**D**). A feature of these islands is their complex wildland–urban interfaces (**E**,**F**). The locations of the capitals of British Columbia (Victoria) and Tasmania (Hobart), and the regional towns of Port Alberni (population 18,000) and Launceston (population 85,000), are also indicated (**A**,**B**). Note that the vegetation maps do not depict intermixes of Garry woodlands in coastal Douglas-fir or differentiate between dry and wet *Eucalyptus* forest.

2. Vancouver Island—Reliance on Mechanical Thinning and Pile Burning

Vancouver Island (area = 31,285 km^2, population = 760,000) is located off the west coast of mainland British Columbia, Canada. It is heavily forested and spans a steep precipitation gradient from west to east (Figure 1C). Prior to settlement by Europeans, old-growth temperate rainforests composed of cedars and hemlocks covered much of the island, with Douglas-fir forests and Garry oak woodlands dominating the east coast [23]. These vegetation assemblages developed during the Holocene, as recently as 6000 years ago [24], and have been shaped by Indigenous use of landscape fire in the past 2000 years [25]. Fire weather on the island is controlled by a seasonal shift in the subtropical high-pressure cell northward along the Pacific coast, which results in a substantive summer water deficit. Summer high-pressure cells result in strong outflow winds, low precipitation, and low relative humidity, which elevate wildfire risk. The occurrence of dangerous fire weather has been increasing in the recent past (Figure 2A), with extreme wildfire danger persisting for more than 60 days in four of the past 20 years. Prolonged drought and high temperatures in 2015 saw a record 25,000 ha of forests burned in the Coast Fire Zone of British Columbia, which includes Vancouver Island.

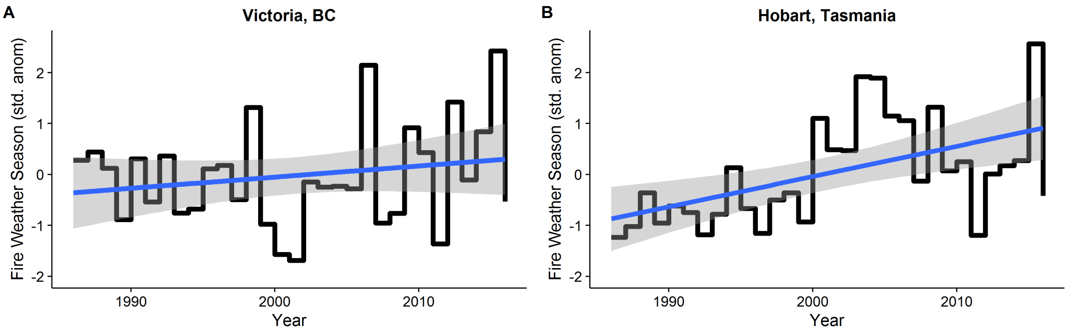


Figure 2. Trends in wildfire season length for Victoria, British Columbia (**A**) and Hobart, Tasmania (**B**) from 1986 to 2016. While there is considerable inter-annual variation in an ensemble metric of wildfire season length based on previous work [7] (expressed as a standardized anomaly, standard deviation from the 1979 to 2013 historic mean), these data show a steady increase in response to climate change.

Victoria (population = 370,000) is the capital city of British Columbia, which is surrounded by forested parks and the watersheds that supply municipal drinking water (Figure 1). The resulting WUI is complex and dispersed across approximately 700 km^2. Records indicate that almost 80% of the wildfires around greater Victoria have been ignited by humans [18]. These fires have typically burned small areas due to effective detection and suppression [26], but the wildfire risk is increasing due to climate change, increased anthropogenic ignitions, and greater abundance of hazardous wildland fuels resulting from wildfire exclusion and regeneration of second-growth forests after logging (Figure 2A). Community wildfire protection plans have been developed and are being implemented. These include raising public awareness of wildfire risk, improving the resistance of homes and critical infrastructure, reducing WUI fuels using mechanical thinning, and creating fire breaks at strategic locations in the landscape [27].

Historically, wildfires have been a minor cause of air pollution events on Vancouver Island, although this may change with increased burning driven by climate change. The majority of smoke pollution is derived from residential wood burning and forest management practices. Approximately one third of homes use wood as a primary or supplementary source of space heating, which is driven by its availability, affordability, and Canadian tradition [28]. This generates a substantial amount of air pollution. Indeed, a 2015 emissions inventory for the Comox Valley airshed indicated that 35% of all fine particulate matter ($PM_{2.5}$) was from residential wood burning [29]. Concurrent ambient air quality studies used levoglucosan [30] concentrations to confirm that woodsmoke is a major contributor to the total $PM_{2.5}$ in this region [31,32]. It is important to note that the topography and climate of Vancouver Island favor the pooling of smoke in valleys and along the coast, particularly under inversion conditions. This is well-illustrated by the city of Port Alberni, where severe air pollution occurs in the cooler months due to residential wood burning (Figure 3A). Although the province recently updated its Solid Fuel Burning Domestic Appliance Regulation [33] to address smoke pollution, this has not effectively improved air quality to date. One barrier is the expense of converting to more efficient stoves and the cost and availability of cleaner-burning wood pellets.

Another major source of smoke pollution on Vancouver Island is the burning of woody debris generated by logging and land clearing, mostly in October and November. Traditionally, woody debris was managed by slash burning, where prescribed fires were applied across the cleared landscape. However, this practice has now been replaced by piling woody debris along roadsides and burning the piles under controlled conditions. In some areas, pile burning is also used for debris created by mechanical thinning to reduce wildfire risk at the WUI. Pile burning regularly causes breaches of the provincial 24-h air quality objective for $PM_{2.5}$, which is 25 $\mu g/m^3$. Although ignitions are typically scheduled to minimize the air quality impacts, piles often burn for several days once lit, and smoke can affect large populations over extensive areas. For instance, pile burning contributes 45% to all $PM_{2.5}$ emissions in the aforementioned Comox Valley, though its air quality impacts vary with meteorological conditions [29]. Over the past 25 years, the province has developed and updated its Open Burning Smoke Control Regulation [34] but, once again, air quality problems persist.

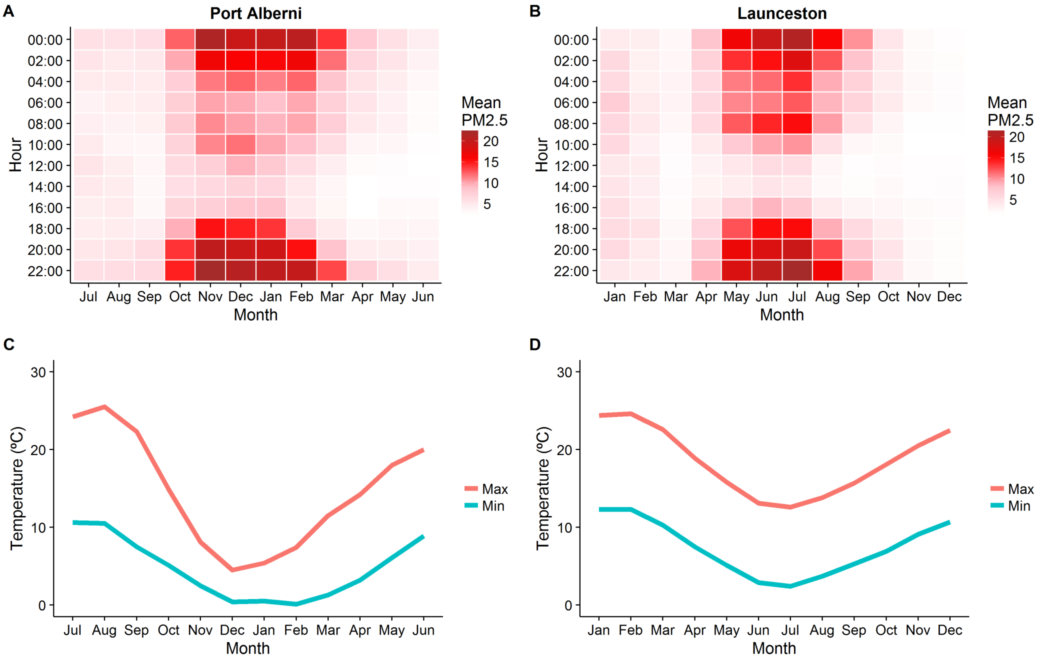


Figure 3. Seasonal and diurnal patterns of fine particulate matter ($PM_{2.5}$) concentrations in Port Alberni, British Columbia (**A**) and Launceston, Tasmania (**B**), averaged from 2009–2016 measurements with beta attenuation monitors. During the winter months (October–March in British Columbia, April–September in Tasmania) residential wood burning is the primary source of $PM_{2.5}$, with morning and evening burning creating the characteristic hourglass figure [32] and dwarfing the effects of smoke from prescribed and wild fires in the summer months. The corresponding mean monthly maximum and minimum air temperatures for these locations are indicated (**C**,**D**).

One alternative to pile burning is the conversion of woody debris into wood pellets or other forms of bioenergy. On the mainland of British Columbia, a large wood pellet industry has developed to salvage forests killed by bark beetles [35]. These facilities could also pelletize woody debris from forestry and mechanical fuel treatments, but Vancouver Island does not yet have a wood pellet plant. Compared with conventional appliances for residential wood burning, modern pellet stoves use less fuel to generate the same amount of heat while emitting much less smoke pollution [36]. Combined with effective incentives for use of residential pellet stoves (as per Johnston et al. [37]), approaches to replace pile burning with pellet production could improve local air quality, particularly in the winter months, improve health, and mitigate the greenhouse gas impacts through more efficient combustion [38,39].

3. Tasmania—Reliance on Prescribed Fire

The island state of Tasmania (area = 68,000 km^2, population = 515,000) is located to the south of the eastern mainland of Australia. Like Vancouver Island, it is dominated by flammable vegetation that spans a steep precipitation gradient from the humid west coast to the dry east coast (Figure 1D). Human set fires have been used across the island for at least 35,000 years, creating a complex mosaic of fire-prone treeless plains, eucalypt savannas, and tall eucalypt forests that integrate with the wildfire-sensitive temperate rainforest [40]. The capital city of Hobart (population = 225,000) is topographically constrained by an estuary at the end of a valley with steep slopes. This creates a long and complex WUI spanning approximately 120 km. The valley periodically funnels strong, hot, northerly winds originating from the center of the Australian continent. These become extremely dry due to the Foehen effect, which is caused by the high plateau in the middle of Tasmania, creating dangerous fire weather [41]. In 1967, such extreme conditions sustained a wildfire that destroyed the outer suburbs of Hobart and threatened the center of the city.

Overall, the urban and physical environments expose Hobart to the risk of catastrophic wildfires, which has been recognized by disaster planners [42]. Government guidelines for reducing wildfire risk include modifying structures to resist ember attack and landscaping to reduce the density of flammable vegetation around buildings. However, these guidelines are not enforceable for existing structures. In response to past wildfire disasters in Tasmania [43], there has been increased use of prescribed fire to reduce wildfire risk in dry *Eucalyptus* forests, which typically occur on equatorial slopes and in rain shadow areas around Hobart. This has been combined with the creation of networks of fire breaks to provide additional protection for urban developments. It is important to note that prescribed fire cannot be applied in wet *Eucalyptus* forests, which typically occur on polar slopes and in moist areas, because they only become flammable under dangerous fire weather conditions [44]. Further, the most effective prescribed fire at the WUI must be applied around assets that require protection, an approach that necessarily causes smoke pollution in populated areas [44].

Continued lengthening of the fire season associated with global climate change is an added complexity (Figure 2B), which reduces the number of days on which prescribed fires can be controlled and the smoke is less likely to be dispersed [45]. Like elsewhere in southern Australia, prescribed fire is controversial in Tasmania because of smoke pollution [46], but mechanical thinning is not widely used at the WUI because of public opposition to removal of trees and associated effects on natural amenity values [47–49]. Another source of smoke pollution in the autumn months is slash burning in the woody debris created by logging *Eucalyptus* forests. Even though the biological basis of this silvicultural practice is poorly understood, foresters assert that slash burning is necessary for effective regeneration of fire-dependent *Eucalyptus* forests, and that smoke is a necessary side effect [50–52].

Smoke from landscape fires and residential wood burning is recognized as a significant environmental health issue in Tasmania [37,53]. Like Vancouver Island, the topography and climate favor nighttime pooling of ambient smoke through the drainage of cold air into valleys, which affects numerous towns and cities. Although prescribed fires are applied on moderate fire weather days, these are commonly associated with poor smoke dispersion due to nighttime temperature inversions and calm conditions. As such, air quality concerns constrain the use of prescribed fires during the weather windows in which they can be controlled. Tasmanian fire managers currently employ a bidding system for the right to use prescribed fire. This system is based on the predicted smoke emissions and dispersion for the number, size, and location of the planned fires. It aims to prevent exceedances of the 25 $\mu g/m^3$ national air quality standard for 24-h average concentrations of $PM_{2.5}$, and is generally considered to be effective [54]. Additionally, communications strategies are being developed to help susceptible individuals manage smoke exposures and health impacts using mainstream media, social media, and a smart-phone application [55].

Like Vancouver Island, Tasmanian air quality is also affected by smoke from residential wood burning [37,53]. Approximately 30% of homes are heated by wood, reflecting the cool climate and the abundance of timber [56,57]. Affordable fuel is an important consideration given the low socioeconomic status of the population, but many residential wood burning appliances are poorly designed and operated. Indeed, emissions from these appliances are the only substantial cause of poor air quality in Tasmania during the cold season. This is well-illustrated by the severe winter smoke pollution in Launceston (Figure 3B), the second-largest city in Tasmania. Wintertime air quality here was significantly improved by a government scheme that enabled households to swap residential wood burning appliances for electric heaters, which resulted in demonstrable public health benefits [37]. In comparison, public education programs designed to improve air quality by improving wood burning practices have had limited success. Space heating using low emissions technologies, such as pellet stoves, can also reduce smoke pollution [58]. However, there is currently limited production of pellets in Tasmania and, consequently, limited adoption of pellet stoves. This situation is unlikely to change without increased incentives.

4. Lessons from Vancouver Island and Tasmania

In Tasmania, prescribed fires are the predominant method of fuels management [59], whereas in British Columbia fuels are commonly managed by mechanical thinning and pile burning [27,60]. In Tasmania, the state has committed an annual expenditure of AU$9 (~US$6.5) million per year from 2018 to 2022 on fuels reduction, nearly all by prescribed fire [61]. By contrast, from 2004–2014, the province of British Columbia spent CA$78 (~US$60) million on mechanical thinning of 68,883 ha at the WUI of high-risk communities, which accounted for less than 10% of the 1.7 million ha identified as being at moderate to high risk [27]. Unlike Tasmania, there is a well-developed wood pellet industry in British Columbia based around salvaging woody debris that cannot be used for other purposes. Strategic combination of elements from both settings could lead to a system of fuels management that would reduce wildfire risk at the WUI, increase resilience to wildfire, improve air quality, and achieve sustainable human co-existence with flammable landscapes. Mechanical thinning is rarely used in Australia compared with North America, but research following the disastrous Black Saturday fires found that removing trees within 40 m of houses had a larger effect on reducing property losses than treatment with prescribed fire [62]. A similar study in California reported a similar result [63].

In addition to aesthetic concerns [48], a major constraint on mechanical thinning is the cost, which exceeds that of using prescribed fire, albeit this depends on any income received from harvested trees, and whether fire is used to reduce fine fuel loads [64,65]. One critical contributor to high mechanical thinning costs is the lack of market for the woody debris that cannot be used for lumber or paper production. In principle, it is possible to use these fuels to produce bioenergy that could be used for domestic and industrial purposes, including water heating, space heating, and electricity generation in surrounding communities [64,66,67]. Both mechanical thinning and bioenergy production are mature technologies, but they are rarely combined to manage wildfire risk because of the economic constraints and lack of incentives [64]. In British Columbia, transportation costs and harvesting fees applied to low-value woody debris create barriers to the development of a robust bioenergy industry. Reforms are needed to generate incentives for innovative use of woody debris to simultaneously reduce wildfire risks and smoke pollution. A similar argument can be made for policy reforms in forest practice and air quality management, combined with incentives and commercial innovation to phase out slash burning, which periodically causes severe air pollution.

5. Leveraging Existing Air Quality Regulations to Drive Innovation in Fuels Management

Regulation of air pollution led by the US, and eventually adopted elsewhere, has driven innovation to reduce emissions from vehicles, industry, and space heating, with marked improvement in regional and urban air quality and corresponding benefits to human health [68,69]. Hubbell et al. (2009) describe the range of strategies and initiatives implemented as part of the US Clean Air Act and the impacts of those interventions on air quality [69]. They include: (1) the establishment of legally binding ambient air quality standards to better protect public health; (2) emissions standards for industrial sources and toxic pollutants; and (3) pollution control programs for vehicles, including technology-forcing emissions restrictions and fuel quality standards. More stringent requirements are implemented in areas not meeting the NAAQS (known as "nonattainment" areas), including the offset of emissions from new industrial sources by reductions from other industrial sources. There are also clauses to prevent areas meeting air quality standards from slipping into nonattainment status. The 1990 US Clean Air Act amendments were globally noteworthy for their adoption of innovative approaches, such as market-based initiatives and emissions cap-and-trade programs, as well as performance-based standards. Taken together, these and other initiatives have resulted in large benefits to population health, such as measured increases in life expectancy [70,71], with the economic benefits consistently exceeding the regulatory costs [72].

Here, we explicitly draw a parallel with these transformative effects on urban airsheds and human health following legally enforceable clean air standards. Drawing on case studies in British Columbia and Tasmania we suggest that regulatory frameworks can drive innovation in fuels management on the temperate WUI if associated with appropriate incentives to reduce air pollution from wildfire, prescribed fire, and residential wood burning. We are not claiming that the current US system is perfectly suited to the challenges of wildfire and fuels management. Based on our experience in Australia where there has been a sharp increase in prescribed fire, however, we are concerned that deregulating smoke pollution from prescribed fires could lead to substantial worsening of air quality and human health outcomes at the temperate WUI [14].

Our concept (Figure 4) involves a combination of regulation and technological advancements akin to the improvements in automobile emissions that followed the development and enforcement of air quality regulations. Examples could include combining prescribed fire with mechanical thinning, promoting the adoption of efficient and low polluting stoves, ensuring housing developments at the WUI are built to resist fire and are thermally efficient, establishing community bioenergy plants, and subsidization of the production of pellets from biomass harvested to reduce fire hazards. Clearly, approaches need be ecologically and socially specific to each context. Innovation could be further driven by regulating air pollution from both wildfires and prescribed fires [21]. It is critical that regulations and incentives to reduce smoke pollution do not lead to perverse outcomes whereby effective fuel management is frustrated in settings where there is minimal health risk. For example, when area-based fees for prescribed fires are decoupled from the actual risk of smoke exposure to surrounding populations [9], such as fuels management conducted away from the WUI.

Figure 4. The effects of smoke pollution on public heath can motivate fuels management, appropriate built environment, and community engagement to achieve sustainable coexistence with flammable landscapes. The status quo (left side) sharply contrasts a plausible fuels management scenario designed to drastically reduce smoke pollution (right side). Artwork credit to Jen Burgess.

In Figure 4 we contrast current approaches (left side) with a plausible fire management scenario designed to drastically reduce smoke pollution (right side). Current fire management is based on aggressive and expensive suppression of high-intensity wildfires (top left circle), where mechanical thinning combined with effective use of prescribed fire would favor lower-intensity wildfires that are less costly to manage (top right circle). The use of pile burning at the WUI to dispose of woody debris (second top left circle) would be replaced by the use of woody debris for production of bioenergy (second top right circle). At the WUI, the dangerous intermix of houses with wildland fuels and the reliance on inefficient residential wood burning (second bottom left circle) would be replaced with urban areas planned and designed using fire resistant materials and appropriate landscaping, where bioenergy is used for electricity generation and pellet stoves (second bottom right circle). Urban environments presently affected by severe smoke pollution for which individuals and public health authorities are ill-prepared (bottom left circle) would become cleaner due to reduced smoke from wildfires, prescribed fires, and residential wood burning, with better preparation though improved public health communications and promotion of effective portable air cleaners [73] (bottom right circle). More fire resilient communities in a less combustible WUI would provide greater opportunity for natural ignitions to burn without demanding large scale and costly fire suppression.

While many would dismiss this vision as unrealistic due to the high costs and sociopolitical challenges associated with such landscape-wide transformation, the history of air quality management and its public health benefits must be considered. Further, these criticisms need to be compared with the extraordinary costs of wildfire disasters, including firefighting, asset losses, and indirect economic impacts such as reduced tourism during wildfire events or smoke episodes. The estimated economic cost of exposure to smoke from landscape fires in the US over a four-year period is between US$10 to US$100 billion [74]. In Tasmania, annual wildland firefighting costs jumped from AU$15 (~US$11) million in 2013 to over AU$52 (~US$39) million in 2016, due to the greater use of aircraft [42]. In the Canadian province of Alberta, the insurance costs for the 2016 Horse River wildfire, which burned into the city of Fort McMurray, have been estimated at CA$3.6 (~US$2.8) billion, while the total economic impact has been estimated at CA$8.9 (US$6.8) billion [75]. The potential impacts of wildfire in British Columbia are understood to be similar to those in Alberta. Indeed, the 2017 season was unprecedented in terms of area burned, cost of suppression, and duration and magnitude of smoke pollution, demonstrating that the CA$78 (~US$60) million spent on strategic wildfire risk management from 2004–2015 has been insufficient to safeguard communities. This is not due to lack of funding for disaster mitigation, however; during the same period the provincial government invested CA$17 (~US$13) billion on seismic upgrades for schools, hospitals, roads, and bridges to reduce the impacts of imminent earthquakes [76]. One research priority should be an understanding the economic costs and benefits of different fire management approaches relative to wildfire, particularly with explicit consideration of the costs of public health harms.

We acknowledge that our emphasis on the public health impacts of smoke pollution has not explicitly considered the greenhouse gas emissions associated with bioenergy technologies, nor the positive role of landscape fire as a vital ecological process. Conceptually, a shift to wood pellets for residential space heating would contribute to reduced fossil fuel use. In Europe and Asia wood pellets are used as a renewable fuel to offset or replace greenhouse gas emissions from fossil fuels. Indeed, this is a prime driver for wood pellet exports from Canada, but transport of wood pellets overseas requires additional energy inputs compared with local use [77].

We are not advocating the exclusion of prescribed fire or wildfire from naturally flammable landscapes. Rather, we are advocating for judicial use of prescribed fire to optimize benefits relative to smoke pollution costs. We strongly recommend moving away from land management practices that generate substantial smoke pollution, such as pile and slash burning. Research has shown that appropriate combinations of mechanical thinning and prescribed fire are most effective at mitigating wildfire risk and then maintaining reduced wildfire risk [78]. We suggest mechanical thinning combined with harvesting of woody debris for wood pellets and other forms of bioenergy. This would provide the opportunity for prescribed fires that generate less smoke and are more likely to meet air quality standards, effectively mitigate wildfire risk, and promote biodiversity at the WUI and in the hinterlands. We acknowledge the need for development of prescribed fire regimes to mitigate wildfire risk and sustain biodiversity that is context-specific and involves trade-offs for different species and ecological processes [79]. Biodiversity can be promoted through the creation of green fire breaks [80], by restoring plant communities, or by creating biodiverse novel ecosystems [81]. Further, landscape design principles at the WUI could be inspired by flammable landscapes managed by Indigenous people creating fire resistant, and biodiverse, vegetation mosaics that are maintained by native herbivores and targeted prescribed fire [82].

6. Conclusions

When compared with other natural disasters, such as major earthquakes, wildfires pose a relatively predictable and manageable risk to human populations. The key to managing wildfire risk lies in routine and ongoing fuels management at the WUI and in the hinterlands. An increasingly advocated approach for managing such fuels is the use of prescribed fire, which is constrained by its bureaucracy, efficacy, practicability, risk and liability, and smoke generation that is known to harm human health. Smoke from all sources necessarily intersects with regulatory frameworks. Therefore, air quality regulations can be leveraged to promote alternate approaches to fire management at the temperate WUI. This could lead to more ecologically and economically sustainable practices that reduce smoke pollution from residential wood burning, pile and slash burning, wildfire and prescribed fires, as well as restoring or creating biodiverse green fire breaks. Cost-benefit analyses that explicitly consider the economic impacts of fire management and domestic smoke pollution on human health are needed as a key step in this process. Rather than exempting emissions from landscape fires, we suggest that existing air quality regulation can be used to drive innovation and investment to improve on current fire management practices. For this approach to succeed, fire managers need to work closely with regulators to craft effective smoke management frameworks that protect public health, reduce fire risk at the WUI, and sustain biodiversity.

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