

Living on a flammable planet: interdisciplinary, cross-scalar and varied cultural lessons, prospects and challenges

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Living on a flammable planet: interdisciplinary, cross-scalar, and varied cultural lessons, prospects, and challenges

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0. Summary

Living with fire is a challenge for human communities because they are influenced by socio-economic, political, ecological, and climatic processes at various spatial and temporal scales. Over the course of two days, the authors discussed how communities could live with fire challenges at local, national, and transnational scales. Exploiting our diverse, international, and interdisciplinary expertise, we outline generalizable properties of fire-adaptive communities in diverse settings where cultural knowledge of fire is rich and diverse. At the national scale, we discussed policy and management challenges for countries that have diminishing fire knowledge, but for whom global climate change will bring new fire problems. Finally, we assessed major fire challenges that transcend national political boundaries, including the health burden of smoke plumes and the climate consequences of wildfires. It is clear that to best address the broad range of fire problems, a holistic wildfire scholarship must develop common agreement in working terms and build across disciplines. We must also communicate our understanding of fire and its importance to the media, politicians, and the general public.

1. Introduction

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4 As the contributions to this issue demonstrate, the role of fire on Earth and the challenges that it poses to
5 human societies are myriad. These challenges cut across particular geographic, social, and temporal scales
6 that require equivalent scientific and policy emphasis. From transnational Earth system impacts [1], to
7 domestic impacts on sovereign nations [2], to impacts on local communities [3], and the individuals who make
8 up communities, the perceptions, decision-making, and prioritisation of policy goals are built upon cultural and
9 historical experiences [4-6] that have legacy effects, lags, and feedbacks across temporal scales [7-12].
10 Although there is a growing literature on building fire-adapted communities [13, 14], it is important to recognize
11 that there is both heterogeneity and variability in the historical, technological, cultural, and environmental
12 contexts in which humans perceive and respond to fire challenges [15], and that in turn these have cross-
13 scalar feedbacks through socio-political structures [2, 16], intergenerational cultural transmission [5], historical
14 ecology of landscapes and biomes [12, 17, 18], and even fire-atmosphere-climate feedbacks [19-21].

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21 Appropriately tackling heterogeneity and cross-scalar issues in human-fire dynamics is challenging, in part,
22 because of the atomised intellectual contexts of fire scholarship today [22]. Most research tends to be
23 undertaken by European, American, or Australian physical or biological scientists, who focus on the costly fire
24 challenges in their industrial or post-industrial societies [13, 14]. These studies tend to focus on national or
25 regional-scales [23, 24], although global analyses are also common [1, 25]. Human dimensions research [26],
26 tends to be ahistorical, treating these fire challenges as exclusively contemporary phenomena for which
27 history is either absent or irrelevant.

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32 Over the course of two days ensconced at Chicheley Hall, our international, interdisciplinary group discussed
33 these issues at three scales. At one scale, we evaluated the lessons learned from community-scale research
34 on living with fire in varied cultural settings. At another scale, our discourse focused on national-scale issues
35 for fire management in economically developed countries with diminishing cultural knowledge of fire, but for
36 whom a warming planet will make fire issues an unavoidable concern, such as the United Kingdom. Finally,
37 we discussed the unique policy challenges posed by transnational fire impacts, particularly the costly effects of
38 wildfire smoke on human health across international borders, and of carbon emissions on global climates. We
39 summarize our discussions below. Although our group was diverse in its disciplinary expertise and geographic
40 experience, we make no claim that our discussion and its summary here are exhaustive. Rather, we aimed to
41 distil our knowledge for lessons across scales, with a unique emphasis on our distinctly British surroundings
42 as well as our varied cultural expertise, and with a concern for modern issues and future challenges.

43 44 45 46 47 48 49 2. Lessons from fire-adapted communities in varied cultural settings

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52 The process of building and sustaining fire-adaptive communities in contemporary landscapes presents a
53 multitude of social and ecological challenges. We identified a suite of common issues that can help
54 communities increase their adaptive capacity to changing fire regimes in the context of larger drivers of
55 environmental, demographic and socio-economic change – hence the term adopted here, ‘fire-adaptive’ rather
56 than ‘fire-adapted’. Building on our collective personal and professional experiences in regions with active fire
57 cultures and recent histories of dealing with socio-ecological fire challenges, our discussions emphasized two
58 domains of human communities and their environments that impact their fire-related adaptive capacity: 1)
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4 knowledge, values, and practice; and 2) landscape relationships. This list of propositions (Table 1) is neither
5 exhaustive nor proscriptive. Rather, it is a generalized set of properties that have given cultures long-standing
6 (multi-millennial, in some cases), apparently sustainable relationships with fire, even in the context of changing
7 climates, technologies, and economic and political relationships.
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11 It is important to note that even in the small sample derived from our discussion group's expertise, landscapes
12 and their associated communities were highly heterogeneous, not just in terms of fire and ecosystem mosaics
13 but in terms of people, their relationship to fire, and how these in turn reflect and affect broader social issues.
14 Similarly, the insertion of fire into a less fire-prone landscape via climate change, vegetation change, or novel
15 human ignition sources may generate new social issues, including disparities of power and equity. For this
16 reason, our list includes not only issues related to biophysical adaptations to fire but also to the ways in which
17 diverse communities of people interact with fire through socioeconomic relationships.
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21 On the basis of current knowledge, we developed a set of propositions that we elaborate below, followed by
22 two community case studies that illustrate how varied fire-adaptive communities can be, as well as their
23 shared properties and contemporary challenges.
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26 27 28 2.1 Knowledge, values, and practice

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30 Fire-adaptive communities will *derive knowledge of how to manage the land from multiple sources and*
31 *perspectives*. Ultimately, sustainable fire management will require place-based solutions but for many
32 communities, formal scientific knowledge is difficult to access, interpret, and when poorly adapted to local
33 circumstances, it may not provide an efficient or appropriate, short-term solution. Traditions of local knowledge
34 and practice provide a wealth of tried and tested information that should be considered in designing local fire
35 management plans [4, 5], and may grant legitimacy to fire management institutions.
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39 Fire-adaptive communities *recognize traditions of place-based knowledge and practices related to fire*.
40 Globally, large numbers of people use fire as a tool to sustain livelihoods in ways that have been handed down
41 across many generations [27]. Examples of livelihood fire-use range from indigenous Australians [4, 28, 29]
42 and North Americans [30-34], South Asian forest dwellers [35], European farmers [36], to hunters, farmers and
43 herders in tropical savannahs [5, 37-41]. People set fires for numerous reasons that often relate to the
44 reduction of socioeconomic risks and improvement of wellbeing. As a result of the long-standing importance of
45 fire use, peoples around the world retain significant traditional, place-based knowledge of fire ecology [27, 31,
46 32]. Such knowledge is critical to designing and maintaining fire-adaptive strategies, and empowering local
47 communities to manage fire locally may be preferable to alternative solutions when long-developed, place-
48 based knowledge and practice is present [5].
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56 Fire-adaptive communities *identify a range of potential fire regimes and how they might differentially affect*
57 *people, ecosystems and the physical environment*. Landscape fire exhibits a broad range of behaviour and
58 effects [42]. In some landscapes, multiple fire regimes may be possible. Choosing the appropriate fire regime
59 to promote or sustain will depend on both long- and short-term social and ecological effects [9, 43-45]. Cultural
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4 values derived from fire-affected landscapes are relative to the preferences and incentives for different social
5 groups and individuals. Choosing which fire regime to promote may encounter resistance from stakeholders
6 with competing interests and values. The classic example of such a dynamic is the forester-shepherd conflict
7 [46, 47], where foresters work to exclude fire to improve tree recruitment and shepherds introduce fire to
8 improve forage. The first step to finding the appropriate fire regime(s) will involve explicit recognition of the
9 variability of options and their differential effects followed by a recognition of potential conflicts of interest and
10 power differentials among the stakeholders.
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15 Fire-adaptive communities are *committed to the long-term maintenance of fire-related ecosystem patterns and*
16 *processes (especially those important to human provisioning and wellbeing)*. It goes without saying that short-
17 term, stop-gap solutions do not represent adaptive ones. To be truly adaptive, communities need to
18 understand and value long-term solutions that may require profound change in how the future is perceived and
19 valued [48]. In short, our observations indicate that fire-adaptive communities need to be well-informed with
20 widespread access to knowledge. Although knowledge equity is necessary for these communities, it is
21 insufficient on its own to enhance fire-related adaptive capacity. Institutions, social rules, and particular socio-
22 ecological interconnections are necessary to promote and maintain desirable coexistence with fire [13]. In
23 many cases, new forms of fire-adaptive governance systems are needed that can transform maladaptive
24 feedbacks between fire and policies into adaptive ones, reversing what has been termed the socio-ecological
25 pathology of wildfire risk [24].
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32 2.2 Landscape relationships

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35 By the term “landscape relationships”, we refer to the network of social and ecological interconnections across
36 scales, as viewed from the perspective of an individual or community. Fire-adaptive communities will have
37 *broad recognition by individuals of the benefits of fire-promoted resources and amenities relative to the*
38 *tradeoffs of burning*. Where individuals gain or perceive benefits from the application of fire that outweigh the
39 immediate costs of burning, both economic and ecological, they are likely to support or initiate burning in the
40 ecosystems in question. Native communities in Northern California support burning in part because many
41 individuals derive livelihoods or identities directly from fire-supported or fire-promoted resources, such as
42 willow and hazel for basketry, or deer for networks of sharing and consumption [31]. Aboriginal people in
43 remote parts of Australia and in the grasslands of Brazil burn in order to increase their hunting efficiencies and
44 to provision networks of sharing and exchange [49, 50]. In the U.S., landowners who have experienced the
45 costs of fire directly or who value its ecological benefits, are more likely to support prescribed burning efforts
46 [51, 52].
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53 Fire-adaptive communities will display *collective action that supports individual benefits from fire management*
54 *while protecting the public good*. In communities with long traditions of fire use, there are social structures in
55 place that facilitate individual decision-making over fire application, as well as providing a system of rights and
56 regulations governing fire at the community, or landscape scale. In some cases, rights to burn are held by
57 individual landowners; in others, rights to burn are held collectively. In most cases, there are strong traditions
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4 or sanctions that specify when, how, and who can burn, and violations of those rights are subject to strong
5 community sanctions, fines, or other punishments [53].
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8 *Management is locally driven but interacts with policies and drivers at multiple scales.* Local, place-based
9 management is arguably the most cost-effective and economical solution to sustain beneficial fire regimes.
10 Ideally, fire management responds to local socioeconomic needs and broader scale market demands, and
11 successfully navigates air-shed health and safety concerns [43]. Furthermore, local management provides
12 legitimacy to programmes that might originate at higher levels of governance hierarchies, thereby creating
13 pathways for sustainable management [54].
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18 Cultural fire relationships are needed to *sustain or restore the socio-ecological networks that are supported*
19 *and derived from the fire regime.* Communities in which fire is embedded culturally rely not just on didactic
20 individual interactions with fire, but use fire to support a network of human social relationships, while
21 recognizing how fire affects ecosystem-wide food webs [9]. Complex linkages between people are generated
22 through sharing and exchanging products from fire-promoted landscapes [50, 55], while those linkages extend
23 outward to connect human social networks with the ecological networks of which they are a part [56].
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28 Fire-adaptive communities may increase fire incidence, frequency, and scope, while reducing the intensity and
29 scale of individual fires, thus *creating vegetated landscape mosaics that produce and control the kinds of fire*
30 *effects desired and acceptable to achieve the fire-generated benefits.* They may reduce the frequency or
31 spread of unintended lightning fires, and may increase landscape diversity by creating smaller-scale
32 vegetation mosaics through pyric succession [12, 57-62]. Anthropogenic fire regimes also may buffer against
33 unpredictable climate-driven changes in fire behaviour and create ecological stability in the face of non-
34 equilibrium vegetation dynamics [38, 63].
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37 38 39 **2.3 Community profiles – fire adapted communities in varied cultural settings**

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42 To illustrate these characteristics in fire-adaptive communities in varied cultural and environmental settings,
43 we provide two brief case studies of European agro-pastoral communities from French Western Pyrenees and
44 Aboriginal communities from Western Australia. Although our group discussions included other Western and
45 non-Western communities that share the aforementioned domains, the case studies below illustrate the
46 shared, generalizable properties of fire-adaptive communities from which we may derive lessons for living with
47 fire now and in the future.
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50 51 52 **2.3.1 French Western Pyrenees**

53 54 *Knowledge, values, and practice*

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56 Over at least the last millennium, ethnically Basque communities developed a particular set of land-use and
57 tenure systems that compliment, rather than combat, the necessary role of fire in maintaining the pastoral
58 landscape. Historically, fire management involved a variety of burning practices centred on the enhancement
59 and maintenance of forage and fibre in seasonally flammable grassland, shrub, and woodland patches. Today,
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4 fire use is mostly limited to low severity pasture burning, and nearly everyone in the community has first-hand
5 experience with fire. The vast majority of community members value fire use and are generally unconcerned
6 with any potential associated costs [36]. Although knowledge and practice of fire-use is still commonplace and
7 is passed on to successive generations, there are fewer and fewer young people choosing farming as a
8 career. As a consequence, the practice is slowly being lost and remaining farmers are struggling to keep up
9 with pastures in need of burning.
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12 *Landscape relationships*

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14 The Western Pyrenees mountains are located in an Atlantic climate zone, receiving up to 1600mm of
15 precipitation annually with cool, wet winters and warm summers with little drought. Around 8,000 years ago,
16 the area was dominated by relatively mesic forest ecosystems and what must have been centennial to
17 millennial fire return intervals [64, 65]. With the introduction and intensification of agricultural and pastoral land-
18 use, high elevation areas (> 900 masl), south facing slopes, and valley bottoms were deforested, thus initiating
19 annual to decadal fire return intervals on more xeric slopes [36, 64, 66]. This activity increased the overall
20 flammability of the landscape by extending the ranges of fire-adapted vegetation. Yet, Pyrenean landscapes
21 and their social components coevolved in adaptive ways that permitted long-term, sustainable settlement and
22 land-use.
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29 Landscape flammability is relatively consistent with topographic constraints on both fire and land-use,
30 considering the limitations for European crop cultivation [67]. Fire-managed resources are also predominantly
31 on communally owned property which constitutes a large proportion of the overall land base. For example, in
32 Larrau, France roughly 9,000 out of 12,500 ha are communal and over 5,000 ha are used as pasture
33 maintained with fire. Private lands that border fire-maintained pastures are buffered by natural and artificial
34 barriers to fire spread. Trails, streams, and other topographic features form fire breaks. In addition, ignitions
35 are timed seasonally and opportunistically during periods when woodlands are too humid to burn. As a
36 consequence, private property is rarely threatened by landscape fire.
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42 With fewer farmers on the landscape, farm abandonment has ensued. Decoupling of fire regimes from land-
43 use and tenure from decreased use-intensity has increased the likelihood of high-severity fires as flammable
44 shrub lands invade former pastures. If current trends continue, fire risks on private property will almost
45 certainly increase. Climate change, bringing warmer and drier summers, may further exacerbate this growing
46 problem.
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50 **2.3.2 Western Australian Aboriginal community**

51 *Knowledge, values, and practice*

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53 Aboriginal people living in the xeric hummock grasslands of Western Australia use fire extensively at
54 landscape scales for many reasons, including to facilitate traditional hunting practices. Burning increases
55 foraging returns for burrowed prey, particularly varanid lizards and other herpetofauna [29, 63, 68]. While
56 some spot fires are lit during the summer months, the vast majority of broadcast fires are ignited during the
57 winter months, when fuels are dry and winds are strong and consistent. In these communities, knowledge
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4 about fire and its ecological effects is widespread and not only gained through everyday practice (children
5 begin burning at a very young age), but passed down through the myth associated with the Dreaming, which
6 instils burning with social, ecological, and ritual significance [69].
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9 *Landscape relationships*

10 In these ecosystems, lightning is seasonally (November-April) a major source of fire ignition, while aboriginal
11 hunters are a major ignition source outside of the monsoon season. Hunting fires mediate climate-driven
12 effects on fire size [4]. Increasing inter-annual variability in rainfall causes temporal and seasonal peaks in fire
13 size under a lightning-driven fire regime, but not in landscapes buffered by indigenous hunting fires. This is
14 due to the differing response of aboriginal hunters to increases in grass growth: hunters light numerous small
15 fires across a wide area as fuels become more continuous, while lightning ignites a few fires that spread
16 widely [4]. Hunters respond to increases in prey density associated with periods of high rainfall, which
17 increases energetic return (calories gained per hour of work expended) from hunting. These increased return
18 rates shift time allocation toward greater investments in such hunting, and the returns from hunting are further
19 invested into social relationships via sharing, creating networks of cooperation and trust among community
20 members [70-72]. Anthropogenic fires are kept small by actively seeking downwind firebreaks or burning
21 patches surrounded by previous burns; individuals are motivated to do so by the threat of social sanctions via
22 traditional punishment rituals for out-of-control burning. Anthropogenic fire increases pyrodiversity – fire-
23 generated ecological heterogeneity and diversity [62] – and reduces both the size of, and distance between
24 unburned patches, reducing the cost of access to post-fire refugia for animals living in the region and more
25 than doubling the density of edge loving species like kangaroo and monitor lizard [49, 68].
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35 Prior to the 1960's, when there were several nomadic groups living in the region, anthropogenic influence was
36 widespread over vast expanses of dune fields and sand plains [73, 74], but today, burning is limited primarily
37 to regions close to communities and vehicle tracks. Aboriginal subsistence fires in the Western Desert thus
38 act, and have acted possibly over millennia, as an intermediate disturbance regime that increases landscape
39 heterogeneity and dampens climate-driven fire cycles. The withdrawal of aboriginal influence over much of the
40 region may have contributed to the widespread animal extinctions of the 20th century [75-77]. The continued
41 maintenance of ecological diversity and traditional knowledge of fire in this remote region is possible due to
42 the lack of primary industry (pastoralism, agriculture), tourism, or urbanization, which in turn reduces sources
43 of conflict over fire and allows aboriginal people to be the primary decision-makers over the timing and
44 patterning of landscape burning. Continuing threats to aboriginal livelihoods make the region increasingly
45 vulnerable to extensive wildfires in the face of climate change, which is causing both increased rainfall and
46 greater interannual variability [78], both of which enhance the risk of extreme fire events [79, 80].
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53 **3. Building fire-adaptive communities in industrialized societies with dwindling fire** 54 **cultures**

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57 In contrast to the parts of the world where experience with fire is commonplace and evolving with directional
58 climate change [81, 82] and changes in human settlement patterns [83], there are heavily populated parts of
59 the world where fire has slipped from the political and cultural consciousness [6]. These are primarily countries
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4 and temperate regions with industrialised, urbanised economies where broad awareness of wildfire is low [84],
5 but wildfire risk is expected to increase with climate change [25, 85]. These areas include Northwest Europe,
6 especially the United Kingdom (U.K.), Netherlands and Germany, and to some extent, the eastern United
7 States and countries such as Sweden, Japan, South Korea and New Zealand. Wildfires occur annually in
8 these areas, but destructive fires are episodic and concentrated during hot, dry, and windy weather conditions
9 [86]. This presents the challenge that political awareness is equally sporadic, falling during wet years, while
10 fuel loads accumulate and the potential for intense fires increases [87] – a temporal disconnect still largely
11 unrecognised by policy-makers in Northwest Europe. Indeed, the fire suppression paradigm in countries like
12 the U.K. indicates a similar disconnect between land management and fire policy [88], the consequences of
13 which are already well known in Southern Europe [89].
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20 In urbanised northwest Europe, there are few truly 'wildland' fires, as most ecosystems are semi-natural,
21 sculpted by millennia of human intervention, including historical modification of forest to open moorland, heath
22 and agricultural habitats by felling and landscape burning [90-92]. Yet cultural awareness of fire has
23 diminished as traditional burning practices have been lost with urbanisation and industrialisation [6, 93]. Fire is
24 an ancient agricultural tool in Europe [67, 94], but has been abandoned in Central Europe and the Baltic
25 countries when compared to the Mediterranean Basin. For instance, in Norway, the heritage of fire
26 management disappeared in the 20th century with the end of heathland burning by traditional farmers,
27 resulting in increased fuel loads [95]. More recently, stubble burning after grain harvests was severely
28 restricted in the U.K. by the Crop Residues (Burning) Act 1993. These examples show a steady loss in
29 understanding of fire benefits and highlight the close linkage between fire regimes and socio-economic
30 transitions [26], such as the move from rural to urban living. Importantly, legislation at the national-scale
31 demonstrates a failure to recognise fire within a socio-ecological framework [13], thus restricting the power of
32 local communities to adapt to fire.
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40 In the most developed areas of the U.K., such as southeast England, the landscape is typically a mosaic of
41 relatively small, discontinuous patches of vegetation within the built environment [96]. This low fuel
42 connectivity means reduced potential for fire to spread, so the impact of a fire is more related to its specific
43 location rather than its spatial extent. Such granularity means the exposure of infrastructure and assets to fire
44 is high, even for small fires. The resulting socio-economic impact is comparable to the issues faced at the
45 wildland-urban interface (WUI) of more fire-prone countries [83, 97, 98]. Moreover, multiple land uses can
46 result in conflicting priorities between the needs of wildfire management and other stakeholder groups [99,
47 100], especially in densely populated areas. We elaborate on this further by exploring the U.K. example in
48 detail.
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53 **3.1 United Kingdom as a case study**

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56 Although it may surprise many residents of temperate regions, countries like the U.K. have a long-established
57 wildfire problem. Ecosystems in the U.K. have experienced wildfires for 100s of millions of years [101] and
58 there is a history of wildfires in the types of ecosystems that dominate today, dating back to the start of the
59 Holocene [102]. Wildfire hazard is predicted to increase over time with changes in climate and land use [103,
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4 104]. Fire and fuels management may help to counter the higher risk of ignition brought by higher
5 temperatures and lower rainfall [105].
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8 The term 'wildland fire' is not used in the U.K. because the landscape is predominantly managed and includes
9 little true wilderness. Most wildfires are started by humans, although this is hard to confirm as fire
10 investigations are rare for non-structural fires [106]. The largest wildfires occur on moorlands and heaths
11 [107], including the most environmentally damaging peat fires [108-110]. Peat fires evoke less political and
12 public concern as their impacts are primarily environmental. While the environment is a priority for amenity
13 groups, such as the National Trust, and water companies, it has a lower rating for Fire and Rescue Services.
14 Therefore, a fire suppression paradigm dominates, with zero tolerance to all fires, even those that are
15 ecologically beneficial. Recurrence intervals of more than five years between major fires means they seldom
16 happen more than once within the political cycle of Parliamentary elections, so wildfire fades from political
17 prominence in wetter years.
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23 The majority of fires are small rural-urban interface incidents on grassland, woodland and agricultural land,
24 where they impact on adjacent properties, human health, and infrastructure [2]. Even relatively small fires can
25 have a major impact on risk to human life and wellbeing, causing economic disruption and ecological damage
26 in areas where amenity is highly prized [111]. Such fires are likely to become more common as demand for
27 housing increases the density of ignition sources as well as demands for fire suppression. Fire therefore
28 needs to be included in the U.K.'s development control planning system. In this respect, wildfire risk
29 management should to be considered in a manner analogous to flood risk management [112]. Although fire is
30 beginning to be included in U.K. agri-environment support schemes, it has yet to infiltrate development control
31 planning [2].
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37 The two polarised narratives of fire as either "good" or "bad" has crystallised around the controversial use of
38 prescribed fire on peat moorland for grouse shooting [109]. Game-keepers are keen to maintain rotational
39 burning of heather while conservation groups are anxious to avoid fire-damage to biodiversity, nesting birds or
40 water quality [113, 114]. Smouldering peat fires [110, 115] are a particular concern for moorland carbon
41 stores, peat erosion, biodiversity, air and landscape quality, and discoloration of drinking water, resulting in the
42 need for costly ecological restoration [116]. Preventing 'severe wildfire' is therefore a unifying goal that both
43 game-keepers and amenity groups can agree upon, although they differ in their preferred risk-reduction
44 strategies (fuel management by prescribed burning versus ecological resilience by rewetting). Nevertheless,
45 controlled burning remains part of an accepted land management regime, and could be argued as a historical
46 practice that is part of the U.K.'s cultural identity, particularly in areas such as the New Forest, or Dartmoor
47 and where moorland management for game practices are concerned.
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53 Awareness of wildfire risk is highest at a local scale, where conflicts of interest between stakeholders are
54 sometimes overcome by collaborative fire groups made up of firefighters, landowners and amenity
55 associations [117]. These fire groups and their national equivalents, the Scottish and the England Wales and
56 Wildfire Forums, have emerged as an informal cross-sector solution to fragmented governance and national
57 policy [2].
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5 Global warming and ongoing demographic, settlement, and cultural changes mean that the wildfire problem in
6 the U.K. will continue to evolve over the coming century. Whereas climate change may make parts of the U.K.
7 more fire prone, the decline in traditional rural culture means diminishing cultural knowledge, values, and
8 practices associated with fire. Ongoing expansion of peri-urban settlement into rural landscapes will add new
9 stakeholder conflicts. The rural-urban interface (or WUI, in other contexts) will require landscape-scale risk-
10 and fire-management [118, 119], but if lessons are to be learned from fire-prone settings, management will
11 also need to be local. For some contexts, wildfire risk is being integrated into an overall land management
12 regime [105]. This requires institutional and community recognition that not all fire is damaging – controlled
13 fire is a traditional management tool in fire-tolerant ecosystems and indeed beneficial to many ecosystems
14 [120]. Fire must be viewed holistically, with both managed fire and wildfire lying on a continuum in terms of
15 severity and frequency. Resumption of traditional burning practices in appropriate areas may be one
16 approach to managing landscapes to reduce the risk of catastrophic fires and the associated environmental
17 damage and social disruption. Whether fire impacts are deemed good or bad depends on the desired
18 outcome, and so where multiple land use dominates, there are cultural judgements to be made about which
19 ecosystem services are to be prioritised. To enable long-term, adaptive capacity to a future with fire (and its
20 attendant uncertainties), national policy may need to provide incentives and structures for local communities to
21 develop the knowledge, values, and practices necessary to provide legitimate, appropriate solutions to
22 evolving fire problems. To this end, widespread access to knowledge is key, although in the U.K., much more
23 research is required (Supplementary Online Material).
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33 4. Transnational issues for fire in a warming world 34 35

36 In some countries, such as the U.K., episodic national interest in wildfire problems result in little policy action,
37 whereas in fire-prone countries, policy can generate socio-ecological pathologies [24]. We have made the
38 case that in varied cultural and ecological settings, adaptive capacity for coexisting with wildfire is greatest
39 when knowledge, values, and practices are locally situated and in which landscape relationships link
40 individuals in networks of ecological, health, and economic benefits of the supported fire regime. However,
41 wildfire also creates challenges that transcend individual communities and international boundaries. For
42 terrestrial borders, fire can literally migrate from one country to the next, although the aerial by-products of
43 wildfire have the furthest geographic reach and cause the greatest challenge to human health and to Earth's
44 climate. Inaction is clearly undesirable, and we look for models of transboundary governance strategies
45 developed in other contexts. Finally, we identify the need for better integration of research and scholarship on
46 fire issues that itself transcends international borders.
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53 **4.1 Wildfires and emissions** 54

55 *4.1.1 Direct impacts of smoke on public health* 56

57 Fire emissions are a complex and dynamic mixture of hundreds of different compounds including gases and
58 aerosols. The predominant gas is carbon dioxide but others include oxides of nitrogen and sulphur, carbon
59 monoxide and methane. The smoke from fires also contains the constituents for the formation of secondary
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4 pollutants, including ground-level ozone. Many of these gases have well recognized adverse health impacts.
5 Emitted aerosols include elemental and organic carbon compounds and are often measured as the mass of
6 suspended particulate matter (PM). PM is the constituent most strongly associated with adverse health
7 impacts, including the exacerbation of cardiorespiratory diseases and increased mortality [121]. When smoke
8 emissions affect large human populations they present a serious public health hazard. Smoke from
9 smouldering combustion in deep peat or dense forest can linger for weeks under inversions and create
10 especially severe and prolonged pollution episodes. While most public health experts advocate for reduction
11 in particulate air pollution wherever possible, a world without landscape fire is neither possible nor desirable.
12 Not all fires are equally bad. There are many instances where fires will occur and may be more
13 environmentally benign than the alternatives and where fires are a passing phenomenon of a season, which
14 should be accommodated to mitigate future fire threats. The proper issue is one of balance and resilience.
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20 Documented transnational smoke issues have occurred in Europe, North America and elsewhere. For
21 example, agricultural burning in Eastern Europe can send smoke to the Scandinavian countries [122], and
22 wildfires in Canada have cast palls in the eastern U.S. However, the most notorious transboundary offense is
23 the Southeast Asian "haze" that has resulted for several decades from the burning of tropical rainforest and
24 peatlands, largely driven by land conversion into large-scale palm oil and pulpwood plantations [123]. This is
25 a human-created disaster that involves both feckless burning and public health impacts, and exemplifies the
26 need for governance across national borders. Fire emissions from tropical deforestation and peat conversion
27 locally in Southeast Asia have the potential to contribute to serious regional health problems from smoke
28 exposure in countries beyond those where the fires are located [121, 124], with the haze of particulate matter
29 and gasses transported hundreds of kilometres [42]. For example in 1997, the fires in Indonesia increased
30 hospital admissions [125] and mortality [126] in Malaysia, and infant and neonatal deaths in Indonesia [127].
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37 *4.1.2 Wildfire impacts on climate*

38 Emissions of greenhouse gases from wildfires are often considered carbon neutral, with emissions rapidly
39 sequestered in subsequent vegetation regrowth; notably within savannah ecosystems [128]. However, when
40 such fires lead to a shift in vegetation or a loss of soil carbon sequestered over millennia, emissions contribute
41 to global climate forcing [129] and can have global climate impacts [1]. Peatlands represent one such global
42 carbon store that has accumulated over millennia and is at risk from deep burning fires [123]. In 1997,
43 emissions of 0.81-2.57 Gt carbon from fires on carbon-rich peats in Indonesia were equivalent to 13-40% of
44 global fossil fuel emissions [130]. While the average annual release of 0.19 Gt of carbon from southeast Asia
45 peatland fires over the last 19 years (1997-2014; [131]) by itself is not likely to exert major radiative forcing, it
46 will add to the atmospheric burden of greenhouse gases, and might become amplified if large fires become
47 more frequent with climate change. Further, northern peatlands cover a greater area, and contain potentially
48 five times more soil carbon (500-600 Gt) than tropical peatlands [132]. These high latitudes are the fastest
49 warming regions on the planet, with temperatures increasing at approximately twice the global average [133].
50 Changes in the hydrological cycle through industrial development [134] and drying out of peat associated with
51 climate change [135], coupled with high severity fire, is likely to result in the degradation of boreal peatland
52 ecosystems and losses of long-term carbon storage [108, 136]. In addition to these impacts on carbon
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4 emissions and storage, plumes of smoke haze circumnavigate the globe, altering the radiative balance of the
5 atmosphere [137] and affect regional rainfall patterns [138].
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8 4.2 Governance of transnational issues 9

10 A fundamental challenge for addressing transnational and trans-border fire issues is the governance of the
11 complex, adaptive system of interconnected human, ecological, and climatic actors that are present but
12 divided across disconnected political jurisdictions. The term 'governance', in contrast with 'government',
13 suggests collections of diverse parties with different levels of authority at local, regional, national and
14 international levels who aim to address complex problems across borders [139, 140], such as the Southeast
15 Asian haze issue [141]. Globally, we have no practical models for managing or governing the multiple drivers
16 and consequences of fire across borders.
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22 Our discussion suggests that the potential directions forward are threefold. First, we need to better
23 understand how current models for governing complex problems across borders could be applicable to the
24 challenge of fire. For instance, drawing from parallel policy arenas such as global water governance [140,
25 142-145] could be productive. These arenas already must consider how local actions influence regional to
26 global processes and vice versa. Loosely coupled governance arrangements that can link local, regional,
27 national and international efforts may be most promising [145], especially if done via mechanisms that are
28 adaptive to both local conditions and rapidly changing environments. The ability to incorporate and respect
29 different kinds of knowledge, including traditional knowledge, local knowledge and science, while embracing
30 uncertainty and the need for flexibility to adapt to dynamic conditions, are key design features for longer-term
31 sustainability [140].
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37 Second, existing transboundary agreements that already apply to fire research and fire management could be
38 considered as models for policy solutions. While many of these partnerships pertain to facilitating suppression
39 efforts, they have cultivated relationships that could become a basis for a loose governance system that takes
40 a more proactive look at broader issues related to fire. For instance, resource sharing agreements across
41 borders for personnel, aircraft and other resources as well as the regional fire networks created by the Global
42 Fire Management Center (much of it under United Nation auspices) offer a few pathways.
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47 Third, ongoing negotiations related to the Kyoto Protocol and the recent Paris Climate Accord offer an
48 opportunity to put fire on the management and governance agenda, as opposed to just the science agenda,
49 particularly as a more important consideration in both tropical and boreal contexts.
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53 4.3 Challenges across disciplinary boundaries 54

55 Importantly, there is disconnect between how fire is researched—as a subset of major disciplines—and how it
56 functions in the world and across borders. It has not existed as its own intellectual entity, a situation that
57 creates problems of communication and understanding. Although there was not unanimity among our group
58 on how transdisciplinary integration might be best achieved, or whether such an approach need be given a
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4 name, investment in the nascent field of 'pyrogeography' – the holistic study of fire on Earth [15, 26] – may be
5 one way to provide unity to the varied fire research programs across the globe. Regardless of the label used to
6 describe an integrated domain of fire scholarship, its purview must extend beyond the sciences and
7 engineering to include social sciences and humanities.
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11 A grand unified theory of all these perspectives is not necessary, but clarification on conceptual language and
12 a lexicon sufficient to make communication possible is desirable and is currently missing from the many fields
13 that study fire. For instance, key terms such as fire regimes [9], fire frequency, fire season [146], fire intensity
14 and fire severity [147] are unstable across disciplines. A holistic fire scholarship must develop common
15 agreement in working terms and build across disciplines. An example of such efforts include the adaptation of
16 Pyne's historical narrative of human fire-use [148] into the hypothetical relationships between the 'pyric
17 phases' of Bowman and colleagues [26], some of which are evaluated in by Balch and colleagues [7].
18 Nonetheless, short of a major institutional shakeup of academia, fire researchers will likely have to
19 communicate to two disparate audiences: their colleagues across the fire sciences but also those in their
20 traditional disciplines. Creating the cultural competencies to engage across disciplines in respectful and
21 curious ways would be a hallmark of success for 21st century fire research.
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28 Another indicator of success would be the effectiveness of fire scholarship in supporting cross-scalar adaptive
29 capacity for 21st century fire problems. One of our greatest challenges is communicating our science to non-
30 scientists including the media, politicians and the general public. Often debates about fire are polarized by the
31 media where one view is right and the other wrong and the complexities are rarely addressed [109]. As the
32 climate changes, global populations grow, and settlements and infrastructure expand further into flammable
33 landscapes this will become an increasing problem that needs a fuller discussion among all affected:
34 stakeholders, policy makers, and scientists.
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39 5. Concluding thoughts

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42 What recent decades of research and scholarship has made clear is that both humanity and the Earth have
43 remarkably rich and intertwined fire histories [8, 42, 56]. Imagining that we could live without fire is both folly
44 and impossible. Importantly, our combustion habits – both fossil fuels combustion and landscape burning [6, 7]
45 – ensure that we are building new dynamism into our social-ecological relationship with fire through climate
46 change [25, 81, 85]. We must learn to live with fire, and we can learn quite a bit about the generalizable
47 properties of fire-adaptive communities by expanding our lens beyond Western, industrialized social orders
48 and economies. Such varied cultural lessons should be received with humility and an awareness that cross-
49 scalar interactions in the human realm (economic, social, and political hierarchies) make specific analogies of
50 fire-adaptiveness across contexts problematic. Nonetheless, there are a few governance observations that
51 seem to apply across contexts that are valuable for those settings with and without well-developed cultures of
52 fire. Importantly, communication and knowledge need to move freely through the community and across
53 scales of governance. Decisions about fire-use and fuel manipulation need to be locally legitimate, either
54 through their support of cultural or economic needs of the community or through their enrichment of other
55 social-ecological properties desired by the community. Management and planning need to account for
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4 processes, benefits, and impacts across time-scales: before, during, and after fires. With demographic,
5 economic, and climatic change certain but unpredictable, human-fire relationships must retain sufficient social
6 and ecosystem diversity to provide adaptive capacity and resilience in the face of such changes.
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10 Finally, it was clear from our discussion that fire scholarship is reaching a watershed moment where the
11 potential of an integrated realm of fire science, ecology, social science, engineering, and humanities may be
12 achievable. Although there was significant enthusiasm for the recognition of 'pyrogeography' as a
13 transdisciplinary umbrella under which fire scholarship could unite, unanimity was not achieved in support of
14 this label. With the lack of significant alternatives, however, pyrogeography may yet be the field that begins to
15 unify the disparate threads of fire scholarship. The breadth and diversity of scholarship represented in the
16 contributions to this special issue all fit comfortably within the pyrogeography rubric and this collection of
17 papers may serve as a springboard from which pyrogeography continues to grow.
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20 21 22 **Acknowledgments**

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28 Nicholas Walding, and Martin Wooster. We would also like to thank Deborah Martin for her contributions to our
29 discussions.
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31

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34 All listed authors, including the Fire and Mankind Discussion Group, contributed to the discussion upon which this paper is
35 based and contributed content, references, and insight in drafting the section texts. MRC and BRJ led the discussion and
36 drafted the section on the community-scale adaptiveness; JA and JM led the discussion and drafted the section on the
37 United Kingdom and less fire-prone settings, FHJ and TS led the discussion and drafted the section on transnational
38 issues. RBB wrote the case study on Western Australia. MRC wrote the case study on the Pyrenees. CIR, ACS, CMB,
39 WGC assembled the final version of the paper.
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41

42 43 **Competing Interests**

44 *We have no competing interests*
45

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Tables

Table 1. Domains and characteristics of fire-adaptive communities

Knowledge, values, and practices (of individuals and the community as a whole)

- Derives knowledge of how to manage the land from multiple sources and perspectives
- Recognizes traditions of place-based knowledge and practices related to fire
- Identifies a range of potential fire regimes and how they might differentially affect people, ecosystems and the physical environment
- Committed to the long-term maintenance of fire-related ecosystem patterns and processes (especially those important to human provisioning and wellbeing)

Landscape relationships (socio-ecological interconnections within and across scales)

- Broad recognition by individuals of the benefits of fire-promoted resources and amenities
- Collective action supports individual benefits from fire management while protecting the public good
- Management is locally driven but interacts with policies and drivers at multiple scales
- Identifies the socio-ecological networks that are supported and derived from the fire regime
- Sustains or restores important cultural and economic relationships with fire and fire-dependent resources
- Creates vegetated landscape mosaics that produce and control the kinds of fire effects desired to achieve the above

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