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At the nexus of fire, water and society

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The societal risks of water scarcity and water-quality impairment have received considerable attention, evidenced by recent analyses of these topics by the 2030 Water Resources Group, the United Nations and the World Economic Forum. What are the effects of fire on the predicted water scarcity and declines in water quality? Drinking water supplies for humans, the emphasis of this exploration, are derived from several land cover types, including forests, grasslands and peatlands, which are vulnerable to fire. In the last two decades, fires have affected the water supply catchments of Denver (CO) and other southwestern US cities, and four major Australian cities including Sydney, Canberra, Adelaide and Melbourne. In the same time period, several, though not all, national, regional and global water assessments have included fire in evaluations of the risks that affect water supplies. The objective of this discussion is to explore the nexus of fire, water and society with the hope that a more explicit understanding of fire effects on water supplies will encourage the incorporation of fire into future assessments of water supplies, into the pyrogeography conceptual framework and into planning efforts directed at water resiliency.

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

1. Introduction

Fire, water and society are inextricably linked. Water, in the form of rain, snow and fog, nurtures plant life and soil microbiota and replenishes soil moisture, allowing the growth of vegetation that becomes the fuel that is combusted during fire. Forests yield 40% of the water for the world's largest 100 cities and grasslands yield 20%, according to a 2014 report by The Nature Conservancy [1]. Peatlands, while not explicitly mentioned in the report, provide water for several areas, including the city of Dublin, Ireland and 70% of Great Britain [2]. All of these land cover types are susceptible to fire. This susceptibility is increased by the absence or scarcity of water, i.e. drought or low-rainfall conditions [3].

Increasing attention is being directed towards a global understanding of the risks facing water supplies for humans. Water scarcity has been identified as a pressing issue by the 2030 Water Resources Group [4], the 2005 Millennium Ecosystem Assessment [5], the United Nations [6,7] and university groups [8,9]. The 2005 Millennium Ecosystem Assessment estimated that half of the world's population will live in water-stressed basins by 2025 [5,10]. In 2015, the World Economic Forum placed water crises, defined as significant declines in water quality and quantity, at the top of its list of global risks that have the greatest potential impacts on society [11]. What is the contribution of fire to predicted water scarcity and declines in water quality? A comparison of the global maps that depict current and future water scarcity and average area burned (figure 1) shows that many areas of the globe are experiencing both water shortages and high fire activity, strongly suggesting that these areas may be the most vulnerable to post-fire effects on water supplies. Impairment of water for its desired usage is considered a type of water scarcity [13]. For example, water quality effects after fires near Fort Collins (CO), USA prevented the use of stream water as a drinking water source for 300 000 people during a three-month period after the fires [14]. During this period, the water provider accessed alternate water sources, one of the adaptation strategies discussed below.

Many climate change predictions point to increasing stress on water supplies as a result of higher temperatures, greater evaporation rates, earlier snowmelt,

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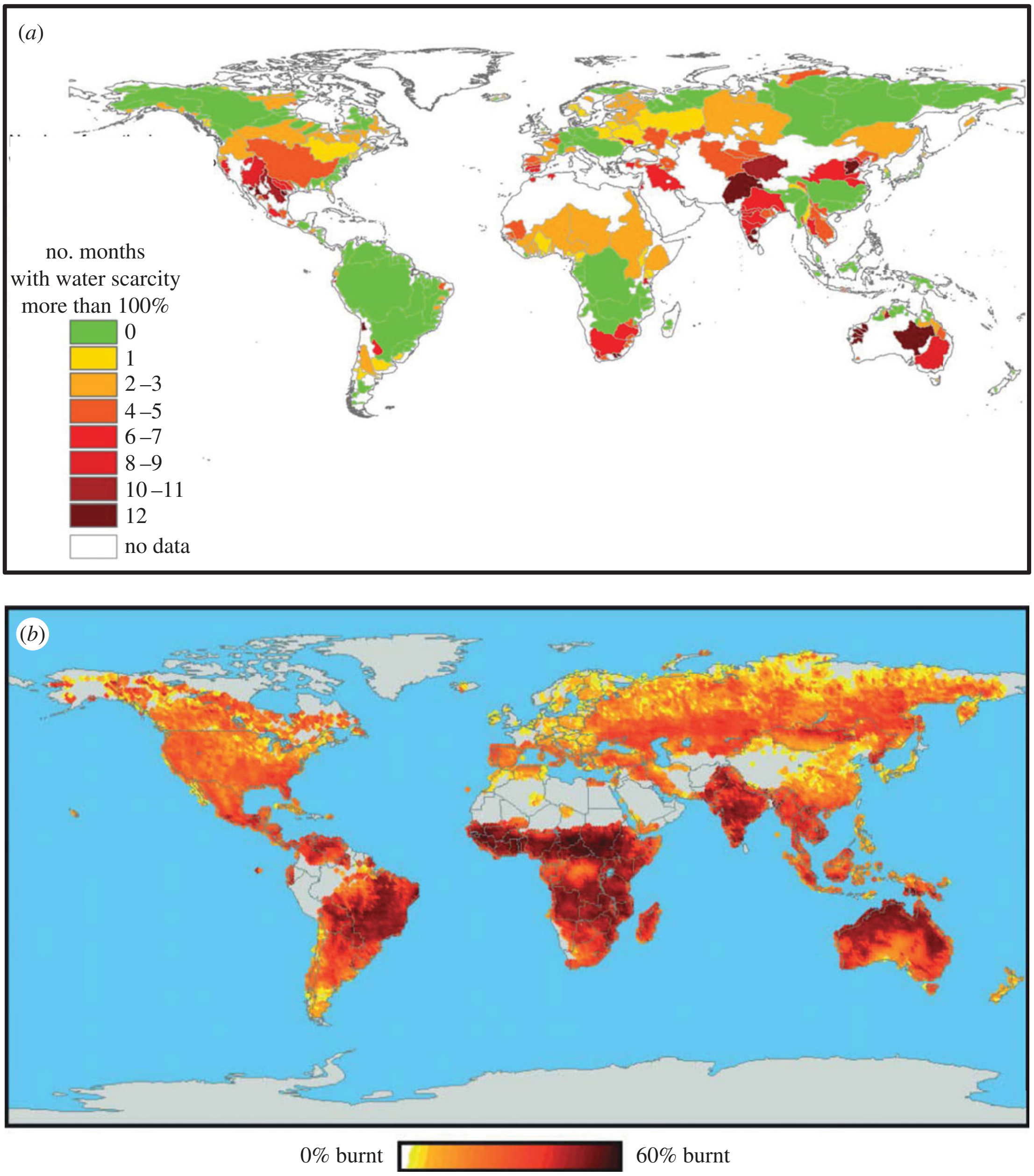

Figure 1. Comparison of global maps showing (*a*) water scarcity as indicated by the number of months during the year in which the consumptive use of ground- and surface-water flows exceeds natural river and groundwater flows (minus environmental flows) for the world's major river basins, based on the period 1996–2005 [9], and (*b*) average annual area burned for the period 1960–2000 [12]. (*b*) Adapted from [12] with permission from CSIRO Publishing.

either increases or decreases in total precipitation and more days with heavy precipitation [15]. Fire is one of the stressors that impacts water, and fire activity is expected to increase with predicted increases in area burned and length of the fire season [12,16]. To date, there have been several examples of post-fire effects on the water supplies of major cities that are located in areas with some pre-existing degree of water scarcity. Effects of fire have been experienced in the water supply catchments of Denver (CO) (fires in 1996 and 2002) [17] and several other cities in the southwestern USA [18], and the four Australian cities of Sydney (2001 fire), Canberra (2003 fire), Adelaide (2007 fire) and Melbourne (2009 fire) [19,20]. Water providers in these cities have incurred high costs (e.g. Denver, $26 million USD [17]; Canberra, $38 million AUD [20]) to restore the function of the water collection, storage, and treatment and distribution components of their water supply infrastructure or to build new facilities. Because of the growing list of cities and communities that have experienced both short- and long-term effects of fires on their water supplies, water merits attention in our exploration of the interaction of fire and mankind. The scope of this discussion is limited to fire effects on drinking water supplies derived from rivers, lakes and reservoirs. The objective of this exploration of the nexus of fire, water and society is to provide an explicit understanding of fire effects on water supplies to encourage the incorporation of fire into future assessments of water supplies, into the pyrogeography conceptual framework and into planning efforts directed at water resilience.

2. Post-fire hydrology, water quality and drinking water supplies

The combustion of biomass is the direct link between fire and effects on water supplies. Fires combust or alter several biomass components (e.g. trees, shrubs, grasses, litter, duff, soil organic matter, peat deposits) of a catchment that are responsible for the mediation of the flow and storage of water. Water is the driver of several post-fire processes that affect society, including flood-inducing runoff and subsequent erosion, and is the medium that transports chemical constituents and potential pollutants through the catchment and downstream of a burned area. Combustion products from fire include burned vegetation (ash and charcoal [21,22]), exogenous chemicals from long-range (transboundary) and long-term atmospheric deposition that have accumulated in water supply catchments (e.g. mercury [23–25]) and pollutants from the combustion of buildings (e.g. arsenic, chromium, lead; [26,27]). These products, which have the potential to impair water quality, can end up in drinking water supplies through atmospheric deposition while fires are burning or conveyed from hillslopes by post-fire runoff. The regrowth of biomass after fire may influence water availability, because growing vegetation affects the water balance in a catchment through changes in interception, storage, evapotranspiration and soil moisture [28–30]. In snow-dominated catchments, the combustion of the forest canopy and the deposition of charred material on the snow surface can lead to changes in the amount and timing of snowmelt [31]. An emerging perspective is that short-term (approx. 10 years) increases in water yield, usually in the form of stream base flow, could be used to augment water supplies [32].

In the last 100 years, considerable research has been conducted on post-fire hydrologic and water-quality responses, primarily in forested catchments in Australia, Canada, Europe and the USA. Fewer studies of the effects of peatland fires on water supplies exist compared to the number of studies in forested water supply catchments [33,34]. Though groundwater constitutes 25–40% of the global drinking water supply [35], very little research has been conducted on fire effects on this drinking water source [36]. The responses of catchments burned by fires are highly variable in space and time. This variability means it is challenging to compare fire effects in different geographical areas [20,37], though there are efforts to develop post-fire hydrogeomorphic response frameworks to facilitate such comparisons [38–40]. Observed post-fire effects range from no observed change in stream hydrology or chemistry to higher peak flows, base flow, suspended sediment (also reported as turbidity) and bedload [41,42], and increases in several chemical constituents such as nutrients, dissolved organic carbon (DOC), heavy metals and polycyclic aromatic hydrocarbons (PAHs) [43–47]. Variations in post-fire hydrology and water quality can only be captured by high-frequency water sampling that includes storm sampling [20], a point reiterated in case studies in the US states of Arizona [48], New Mexico [49] and Colorado [47,50].

In the days to months after fires, post-fire hydrologic and chemical responses appear to be controlled by rain characteristics and the amount of surface runoff [38]. When post-fire overland flow is small, fewer post-fire changes are observed. For example, the duff layer remaining after a high-intensity crown fire in a lodgepole pine (*Pinus contorta*) forest in British Columbia, Canada provided storage for infiltrating rainfall, and thus limited the generation of overland flow [51]. Similarly, the presence of macropores (e.g. ant holes [52,53]) or megapores (e.g. stump holes or depressions created when fires burn into the root mass, or when the roots are heaved out of the ground when trees fall during a fire or some time thereafter [54]) can reduce the magnitude of post-fire overland flow and hence effects on water supplies.

The time since fire is an important factor in the magnitude of the post-fire response. Recovery of vegetation and soil organic matter mediates runoff from burned areas so the magnitude of post-fire hydrologic and water-quality responses generally decreases with time since fire. Sediment mobilized from hillslopes by post-fire runoff may be preferentially stored within the catchment [55–57]. This stored sediment may stay within the catchment until mobilized by subsequent peak flows [58]. Additionally, stored sediment from previous land-use activities, such as mining, can be mobilized by post-fire overland flow and peak flows [47]. Mining deposits and mine effluents generally contain high concentrations of metals that can be dissolved in water or attached to particulate matter [20,59].

Snow dynamics in burned catchments are complex [31], and some studies have shown increased snow accumulation in burned forests, earlier disappearance of snowpack and increased ablation (removal of snow by melting, evaporation, sublimation or wind). These effects occur partly as a result of the removal of canopy by fire and from blackening of tree boles from charring, and from darkening of the snow surface by deposition of flakes of charred bark and other particulates [60]. Snowmelt will be affected for as long as burned trees dominate the post-fire landscape, and possibly longer depending on vegetation recovery. The timing of the snowmelt peak is critical to the delivery of water to reservoirs [61].

No clear pattern exists for fire effects on reservoirs. Some reservoirs experience no fire-related changes while others experience effects that persist for months to decades [20]. During post-fire floods, streams can deliver bedload (generally coarse sediment), suspended sediment (turbidity) and debris to reservoirs. Post-fire inputs of chemical constituents derived from ash and the underlying soil can lead to long-term effects on water-storage reservoirs [62]. It has been estimated that there are 16.7 million reservoirs globally [63]. Only one study has attempted to identify reservoirs in the western USA that are at risk from post-fire sedimentation [64], pointing to a data gap in our assessment of long-term effects of fire on water supplies. There is a shortage of quantitative measurements of the downstream extent and persistence of effects of water and sediment conveyed from burned catchments. In Colorado, detailed measurements of the post-fire bathymetry of a water supply reservoir allowed the calculation of the volume of sediment transported from two burned catchments (one 18 km upstream, the other 5 km upstream) [55]. Measurements after a fire in California, USA detected changes in suspended sediment in a reservoir 160 km downstream of the burned area [65] and a recent study in New Mexico [49] detected elevated values of specific conductance and small changes in turbidity at a site approximately 120 km downstream of a burned area during and four months after the largest fire recorded in the state (approx. 63 370 ha).

Post-fire hydrologic and chemical changes can present operational and treatment challenges to water providers. These challenges can take place while a fire is burning, and in the short- (days to months) and long-term (decades) periods after fire ([14,18,20,37,47,59]; table 1). Operational issues include loss of electricity, communications and access to facilities, and damage to infrastructure. Treatment issues relate to increases in discharge compared with pre-fire conditions and the presence of soil, sediment and combustion products entrained in runoff. The constituents in post-fire runoff that create the most concern are suspended sediment (turbidity),

Table 1. Summary of challenges to water providers as a result of fire.

time frame	challenges	references
active fire period	difficulty reaching water facilities loss of electricity and communication functions physical damage to infrastructure loss of water pressure accidental water contamination from firefighting chemicals additional personnel costs	[18,66]
short-term post-fire (days to months)	treatment issues related to high turbidity, DOC, nutrients, manganese, iron, taste issues (table 2) increased risk of algal and cyanobacterial blooms in reservoirs floating charcoal and debris in reservoirs legacy sediments from previous land-use and post-fire deposition mobilized by high peak flows increased personnel, monitoring and water-treatment costs loss of revenue infrastructure damage from sediment and debris damage to distribution system pipes problems repressurizing distribution pipes increased hydrologic and water-quality variability altered seasonality of hydrological and chemical export from burned catchment	[14,17,18,20,37,47,59,66–68]
long-term post-fire (decades)	loss of reservoir capacity seasonal release of manganese from reservoir sediments	[14,64,68]

DOC, chemicals that impart taste to water, nutrients (e.g. nitrogen and phosphorus), manganese and other heavy metals (table 2). For example, increased levels of nutrients in runoff (and possibly subsurface flow) have led to algal blooms in reservoirs in Australia [67]. In the western USA and Australia, increases in turbidity and dissolved manganese concentrations in reservoirs [19,68,69] have led to higher treatment costs to meet drinking water standards. Dredging to remove post-fire sediments from reservoirs to restore capacity and lessen chemical issues is extremely costly (e.g. Denver spent $23 million USD to remove sediment from a critical water supply reservoir). The primary concern related to peatland burning is the potential to increase the release of DOC, particulate organic matter, suspended sediments, aluminium and iron [33,34,70,71]. The presence of DOC can lead to water discoloration [33,34] and the need for more chlorine to achieve adequate disinfection [72]. The reaction of chlorine and DOC in treated water can lead to the formation of potentially carcinogenic tri-halomethanes or other disinfection by-products [14].The presence of metals in the dissolved phase or attached to suspended sediment requires advanced water-treatment processes [20,59].

3. Water resiliency

Discussions about physical water scarcity or vulnerability of water supplies to disturbances (including climate change, fires and storms) often consider the concept of water resiliency. Water resiliency is the capacity of the physical and socio-economic systems related to water resources to withstand disturbances and to adapt to changes and effects through assessment, rapid response and effective recovery strategies [10]. In a detailed analysis of water resiliency, Rockström *et al.* [73] identify three reasons for heightened concern in recent decades about water. The first concern relates to the pace and scale of human pressures on water supplies. The second is that water is the 'first victim' in response to changes in climate, land use and a variety of other stressors. And the third reason is that there is risk of crossing tipping points, where small perturbations trigger large responses [74], leading to ecosystem states, perhaps irreversible, that may affect water supplies. An example of the latter is the abrupt post-fire transition of forests to persistent grasslands or shrublands documented for areas of the south-western USA [75], a shift to land cover types with different water yield characteristics.

Fire is rarely considered in the context of water scarcity. Exceptions are analyses by Wang *et al.* [10] and Robinne *et al.* [76], who use the term 'water security' in their discussion of the value of their global wildfire water exposure index (GWWEI) to pinpoint areas that may be at risk of fire-related effects to water supplies. Pertinent to this discussion of the interaction of fire, water and society are those adaptations that lead to resiliency of the landscapes that yield water and the infrastructure and entities that support water storage, treatment and delivery of water for humans. These adaptions include preparation, response and recovery measures [77], a useful way to categorize existing measures that have been implemented to

Table 2. Effects of fire-related constituents on water-treatment processes and reservoirs. Summary (from [59]): increased coagulant demand, sludge production, oxidant demand, potential to form disinfection by-products, operating costs. (From [68]): need to manage reservoir operations to minimize cyanobacteria and algae growth, need to destratify reservoir to manage anoxia (iron, manganese and nutrients can be released from sediments under anoxic conditions).

constituent	treatment issues	references
suspended sediment (turbidity)	additional settling and filtration required	[14,20,59,68]
DOC	need for additional filtration potential to form disinfection by-products additional sludge production from coagulation processes	
taste issues	problematic; water can smell and taste smoky algae can also contribute to taste and odour issues oxidation or adsorption processes required	
nutrients, e.g. nitrogen	potential to form nitrogen-containing disinfection by-products difficult to maintain adequate disinfection	
manganese	additional oxidation required manganese can be released from reservoir bottom sediments during dredging, by storm events or as a result of anoxia	

Table 3. Adaptations to increase resiliency of water supplies to disruptions by fire. Implementation level: (1) relatively low cost given availability of staff and data; (2) moderate cost and difficulty; and (3) high cost, very difficult owing to legislative, political, monetary and practical constraints.

time frame	adaptation	implementation level
preparation	establish contingency plans	1
	identify alternate water sources	1
	identify critical source-water areas	1
	build collaborations	1
	identify vulnerabilities and system deficiencies	2
	pre-fire fuel thinning	2
	pre-fire modelling to determine areas at greatest risk of flooding, erosion and deposition	2
	develop real time monitoring networks	3
	plan and get permits to construct pre-sedimentation basins	3
response	close water intakes	1
	implement post-fire rehabilitation measures to stabilize hillslopes, channels and infrastructure	2
	install high-frequency chemical and turbidity sensors (ideally with telemetry capability)	2
	post-fire modelling to identify potential flooding, erosion and deposition	3
	construct pre-sedimentation basins	3
recovery	strengthen existing infrastructure	2
	build new infrastructure	3

increase resiliency of water supplies to disruptions by fire (table 3). All of the measures include technical, organizational, social and economic aspects [10,78], considerations that are beyond the scope of this discussion. Several themes emerge from the compilation of adaptation measures (table 3). Some of the suggested adaptations are operational such as establishing contingency plans and alternate water sources prior to disruptions by fire to water supplies, and some include water in the larger context of adaptation to climate change [79,80]. Within this larger context are recommendations to implement education and outreach, analyses of policy and governance, and on-the-ground restoration or conservation using adaptive management techniques, and to develop strong local science-management partnerships and rapidly communicate methods and findings. Large gaps still exist in our knowledge about fire effects on water supplies [20]. For example, water managers and providers need to know the magnitude and timing of post-fire peak flows, whether chemical constituents will arrive at water intakes in the dissolved phase or attached to particulates, and the expected duration of post-fire perturbations to the water supply. Efforts to identify these variables and convey the information to water providers are in their infancy [18,81], and we currently lack comprehensive tools to consider the effects of fire in planning, protecting and creating resilience in our water supplies.

4. Concluding thoughts

Fire should be included in global and regional assessments of catchment vulnerability to the water- and fire-related aspects of climate change, with particular attention to the issue of water scarcity. The vulnerabilities of lakes and reservoirs to post-fire inputs of debris, sediment and chemical constituents should be included in these assessments. Several global assessments have not mentioned fire as a stressor facing catchments [82–85]. This omission of fire in global water risk or threat assessments is also noted by Robinne *et al.* [76]. However, fire has been included in some, but not all, recent regional, national and global assessments of water issues. For example, a study commissioned by the World Bank/World Wildlife Fund Alliance for Forest Conservation and Sustainable Use included fire [86]. The Forests to Faucets project of the US Forest Service [87] explicitly considers threats of fire in US catchments critical to drinking water supply. An assessment of non-point source threats covering the entire USA included post-fire sediment as a water stressor [88]. The World Resources Institute [17] recognized fire risk management as a cost-avoidance measure in a 'natural infrastructure' (i.e. areas that can deliver water-related services with minimal need for the construction of engineered infrastructure) strategy. The Nature Conservancy study [1] of the source-water areas for the world's 100 largest cities considered that forest fuel reduction to mitigate fire effects had a high potential as a conservation strategy to protect the water supplies of major cities in the USA (Fort Collins, Colorado; Oklahoma City, Oklahoma; Oxnard and Santa Cruz, California; Roanoke, Virginia); Cape Town, South Africa; Kumasi, Ghana; and Tijuana, Mexico. A regional assessment in Montana, USA used geospatial analysis and burn probability modelling to predict municipal catchment exposure to wildfire hazard [89]. The recently proposed wildfire water exposure index [76] is the first spatially explicit analysis that assesses the global exposure of surface freshwater resources to fire.

The pyrogeography framework elaborated by Bowman *et al.* [90] and Krawchuk & Moritz [91] could be enhanced by the inclusion of post-fire hydrologic responses into the framework. Pyrogeography is a 'field of inquiry emphasizing an understanding of drivers contributing to fire dynamics and the resulting effects on both human and natural systems' [91, p. 472]. The pyrogeography perspective already encompasses a consideration of 'the nexus between landscape fire and human health and livelihoods' [90, p. 58]. Given that many parts of the globe are already experiencing water shortages and short- and long-term post-fire water supply effects, it is critical to include water and water-mediated processes, both factors in 'human health and livelihoods', as essential components of pyrogeographical studies.

A common theme in discussions about water resources and water scarcity is the need to improve communication between scientists, policy-makers and the public [92,93]. The 'Interaction of Fire and Mankind' meeting sponsored by the Royal Society presented an opportunity to communicate a simplified summary of fire effects on water to an international audience. An example of interchange of ideas at that meeting is provided in the Discussion at the end of this article. The 2015 *United Nations World Water Development Report* states that 'by 2030, the world is projected to face a 40% global water deficit under the business-as-usual scenario…' [85, p. 11]. A tremendous urgency exists to improve societal resiliency in the face of climate changes and novel ecosystem states that may affect water supplies. In 1977, Malin Falkenmark, a scientist renowned for her extensive body of work focused on global water issues, published an article titled, 'Water and mankind: a complex system of mutual interaction' [94]. The time has come to add fire into our efforts to understand the complex system of water and mankind; we are at the nexus of fire, water and society.

5. Meeting discussion

M. Parrington (European Centre for Medium Range Weather Forecasts). Is there a role for Earth Observation data in monitoring the large-scale interactions between fire activity/emissions with water resources/quality? And what is the potential for bridging the scales from *in situ* up to global monitoring? Comment: Martin Wooster gave a good overview of the atmospheric composition and fire monitoring service within the EU Copernicus programme (http://www.copernicus.eu) but this also extends to other aspects of the global environment and provides the potential for linking different processes across the Earth system in near real time.

D.A.M. Concerted effort would be required to link data acquired using remote sensing instruments to data from on-the-ground monitoring of stream water discharge, water quality, air quality (including dry deposition) and rain water chemistry. Integrated datasets that incorporate the measurements from different spatial scales would be extremely valuable. For example, pre-fire remote sensing could be used to monitor the forests that are growing in the area affected by the 1986 accident at the Chernobyl nuclear power plant. Smoke plumes from fires burning the affected forests could be detected using remote sensing and those data could be used to alert down-wind water providers of the potential contamination of water bodies by atmospherically deposited radionuclides [95].

J. Gowler (University of Liverpool). In one of your slides you highlight the great dearth of studies in Africa, outside of South Africa, even though around 70% of global grass burning occurs in the continent. To give a case: Nakuru in Kenya has grown from 100 000 to 400 000 population in a generation, ahead of the growing provision of electricity. In response a charcoal burning industry has arisen 20–40 km away, to fuel the small stoves used in cooking, with inevitable impacts on vegetation, drainages (and possibly on population health, taking up points covered in the talk by Dr Fay Johnston). Are there agencies and initiatives that are well placed to help address these issues across Africa?

D.A.M. The slide to which you refer contained a global map depicting the geographical distribution of papers addressing the impacts of fire, wind and bark beetles on ecosystem services and biodiversity ([96], figure 1). Less than 1% of fire research identified by the authors had been conducted in Africa. Dr Johann Goldammer of the Global Fire Monitoring Center has reminded the author that the compilation by Thom & Seidl [96] only contains articles in the peer-reviewed published literature and misses a body of literature comprised of non–peer reviewed reports on the topic of fire management. That being said, the issue of charcoal production in Africa is profoundly complex. The United Nations, including the Food and Agriculture Organization and United Nations Environment Programme, have projects focused on the issue but it is unclear which agencies can help address this topic across Africa.

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