PHILOSOPHICAL
TRANSACTIONS B

rstb.royalsocietypublishing.org

Opinion piece

Cite this article: Martin DA. 2016
At the nexus of fire, water and society.
Phil. Trans. R. Soc. B **371**: 20150172.
http://dx.doi.org/10.1098/rstb.2015.0172

Accepted: 22 February 2016

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

Subject Areas:
environmental science

Keywords:
water supplies, reservoirs, water resiliency

Author for correspondence:
Deborah A. Martin
e-mail: damartin@usgs.gov

THE ROYAL SOCIETY
PUBLISHING

At the nexus of fire, water and society

Deborah A. Martin

US Geological Survey, 3215 Marine Street, Suite E127, Boulder, CO 80303, USA

DAM, 0000-0001-8237-0838

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,

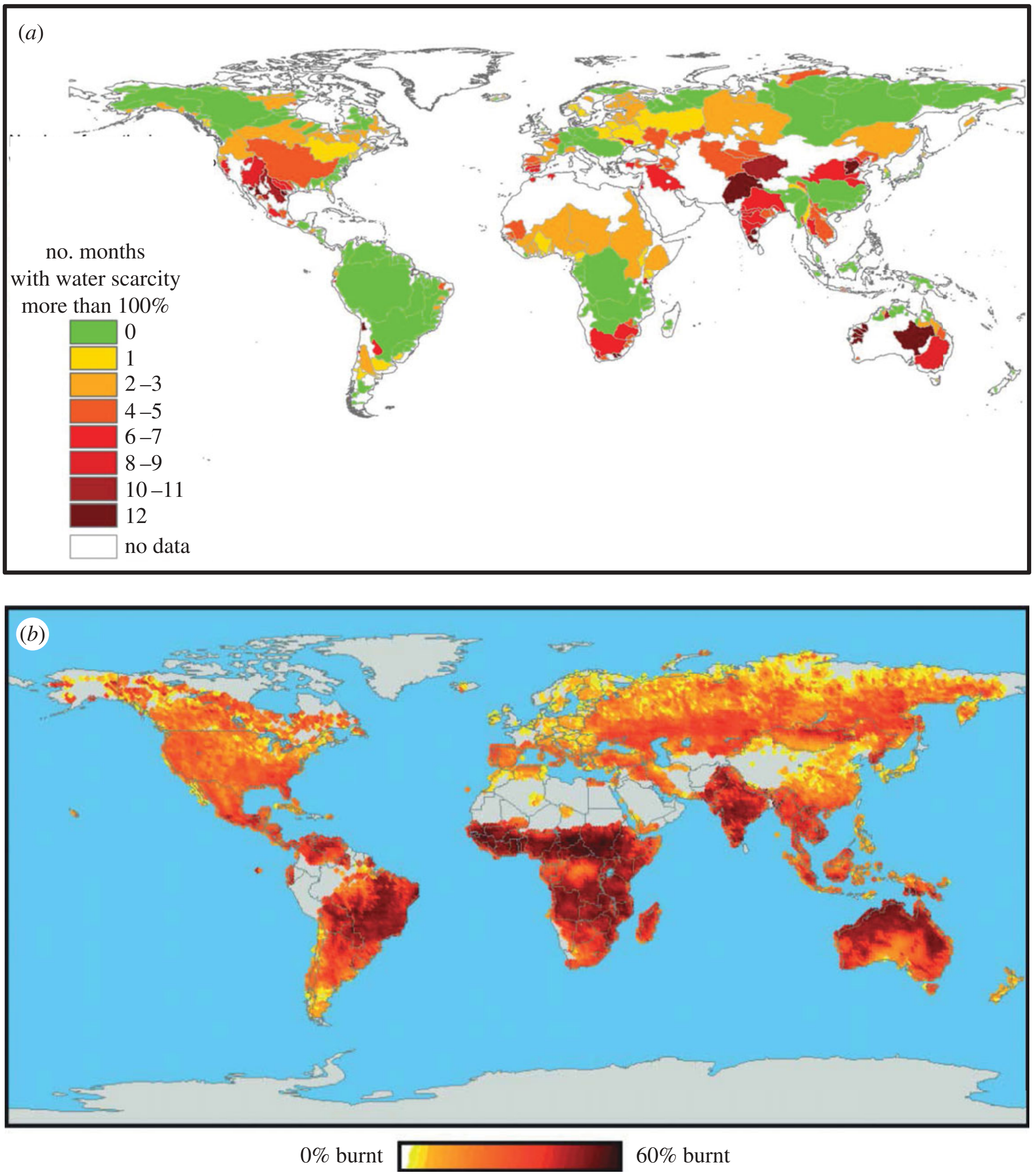

Figure 1. Comparison of global maps showing (*a*) water scarcity as indicated by the number of months during the year in which the consumptive use of ground- and surface-water flows exceeds natural river and groundwater flows (minus environmental flows) for the world's major river basins, based on the 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.

Competing interests. The author declares that she has no competing interests.

Funding. This article is financially supported by the National Research Program of the USGS Water Mission Area and partial funding for travel was generously contributed by the Royal Society.

Acknowledgements. The author wishes to thank the organizers of the Royal Society meeting 'The Interaction of Fire and Mankind'—Andrew Scott, William Chaloner, Claire Belcher and Chris Roos—for the opportunity to give a talk and to participate in stimulating discussions with colleagues both old and new. Thanks to Catriona Ross of the Royal Society for her expert help in all matters that pertained to the meeting in London and the discussion meeting at Chicheley Hall. The author warmly thanks her colleagues at the US Geological Survey (USGS), particularly John Moody for a long collaboration and ongoing explorations of scientific topics, Craig Allen, Julio Betancourt, Sue Cannon, Brian Ebel, Bob Hirsch, Ed Landa, Bob Meade, Sheila Murphy and Bob Stallard. The author extends an appreciative thanks to the Denver Branch of the USGS Library. She would also like to acknowledge the outstanding editorship of Keith Lucey, USGS. A special thanks to Ann Youberg, Arizona Geological Survey, Maria Rosário Costa, Universidade de Trás-os-Montes e Alto Douro, Portugal, Chi Ho Sham, The Cadmus Group, and Johann Goldammer, Global Fire Monitoring Center. Thanks to several colleagues in the US Forest Service including Charlie Luce, Pete Robichaud and Pete Wohlgemuth. The author thanks her international colleagues who have taught her that fire is, indeed, a global phenomenon: Kevin Bladon, Merche Bodí, Artemi Cerdà, Stefan Doerr, Monica Emelko, Patrick Lane, Jorge Mataix-Solera, Petter Nyman, Paulo Pereira, Cristina Santín, Gary Sheridan, Uldis Silins, Micheal Stone, Cathelijne Stoof, Xavi Úbeda, Lea Wittenberg and all of the scientists who have participated in the five International Meetings of Fire Effects on Soil Properties held to date and in the 2013 AGU Chapman Conference, 'Synthesizing Empirical Results to Improve Predictions of Post-wildfire Runoff and Erosion Responses'. And finally, the author gives her heartfelt thanks to her family—Charlie, Pierce, Alex and the rest—for their love and support in all aspects of her life. The author extends her sincere appreciation to Amy Fleetwood, Sheila Murphy and three anonymous reviewers for insightful reviews of this manuscript.

References

1. McDonald RI, Shemie D. 2014 *Urban water blueprint: mapping conservation solutions to the global water challenge*. Washington, DC: The Nature Conservancy.
2. Bonn A *et al.* 2010 *Ecosystem services of peat—phase 1*. Report to Defra. Project code SP0572.
3. Littell JS, Peterson DL, Riley KL, Liu Y, Luce CH. 2016 Fire and drought. In *Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis* (eds JM Vose, JS Clark, CH Luce, T Patel-Weynand), pp. 135–154. General Technical Report WO-93b. Washington, DC: U.S. Department of Agriculture, Forest Service.
4. 2030 Water Resources Group. 2009 *Charting our water future: economic frameworks to inform decision-making*. Washington, DC: McKinsey & Company.
5. Millennium Ecosystem Assessment. 2005 *Ecosystems and human well-being: current state and trends*, vol. 1. Washington, DC: Island Press.
6. UN-Water. 2006 *Coping with Water Scarcity: A strategic issue and priority for system-wide action*. New York, NY: Food and Agriculture Organization of the United Nations.
7. Hoekstra AY, Mekonnen MM. 2011 *Global water scarcity: monthly blue water footprint compared to blue water availability for the world's major river basins*. Value of Water Research Report Series No. 53. Delft, the Netherlands: UNESCO-IHE.
8. Fuller AC, Harhay MO. 2010 Population growth, climate change and water scarcity in the southwestern United States. *Am. J. Environ. Sci.* **6**, 249–252. (doi:10.3844/ajessp.2010.249.252)
9. Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD. 2012 Global monthly water scarcity: blue water footprints versus blue water availability. *PLoS ONE* **7**, e32688. (doi:10.1371/journal.pone.0032688)
10. Wang C-H, Blackmore J, Wang X, Yum K-K, Zhou M, Diaper C, McGregor G, Anticev J. 2009 *Overview of resilience concepts, with application to water resource systems*. eWater Technical Report, Canberra.
11. World Economic Forum. 2015 *Global Risks 2015*, 10th edn. Geneva, Switzerland: World Economic Forum.
12. Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM. 2009 Implications of changing climate for global wildland fire. *Int. J. Wildland Fire* **18**, 483–507. (doi:10.1071/WF08187)
13. Schyns JF, Hoekstra AY, Booij MJ. 2015 Review and classification of indicators of green water availability and scarcity. *Hydrol. Earth Syst. Sci.* **19**, 4581–4608. (doi:10.5194/hess-19-4581-2015)
14. Writer JH, Hohner A, Oropeza J, Schmidt A, Cawley KM, Rosario-Ortiz FL. 2014 Water treatment implications after the High Park Wildfire, Colorado. *J. Am. Water Works Assoc.* **106**, E189–E199. (doi:10.5942/jawwa.2014.106.0055)
15. Intergovernmental Panel on Climate Change. 2007 Climate Change 2007: The Physical Science Basis. In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller). Cambridge, UK: Cambridge University Press.
16. Westerling ALR. 2016 Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Phil. Trans. R. Soc. B* **371**, 20150178. (doi:10.1098/rstb.2015.0178)
17. Gartner T, Mulligan J, Schmidt R, Gunn J (eds). 2013 *Natural Infrastructure: Investing in Forested Landscapes for Source Water Protection in the United States*. Washington, DC: World Resources Institute.
18. Sham CH, Tuccillo ME, Rooke J. 2013 *Effects of wildfire on drinking water utilities and best practices for wildfire risk reduction and mitigation*. Web Report no. 4482. Denver, CO: Water Research Foundation.
19. White I, Wade A, Worthy M, Mueller N, Daniell TM, Wasson R. 2006 The vulnerability of water supply catchments to bushfires: impacts of the January 2003 wildfires on the Australian Capital Territory. *Austral. J. Water Res.* **10**, 179–194.
20. Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Shane Haydon S. 2011 Wildfire effects on water quality in forest catchments: a review with implications for water supply. *J. Hydrol.* **396**, 170–192. (doi:10.1016/j.jhydrol.2010.10.043)
21. Bodí M, Martin DA, Balfour VN, Santín C, Doerr SH, Pereira P, Cerdà A, Mataix-Solera J. 2014 Wildland fire ash: production, composition and eco-hydro-geomorphic effects. *Earth-Sci. Rev.* **130**, 103–127. (doi:10.1016/j.earscirev.2013.12.007)
22. Scott AC. 2010 Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. *Palaeogeogr. Palaeoclim. Palaeoecol.* **291**, 11–39. (doi:10.1016/j.palaeo.2009.12.012)
23. Caldwell CA, Canavan CM, Bloom NS. 2000 Potential effects of forest fire and storm flow on total mercury and methylmercury in sediments of an arid-lands reservoir. *Sci. Total Environ.* **260**, 125–133. (doi:10.1016/S0048-9697(00)00554-4)
24. Biswas A, Blum JD, Keeler GJ. 2008 Mercury storage in surface soils in a central Washington forest and estimated release during the 2001 Rex Creek Fire. *Sci. Total Environ.* **404**, 129–138. (doi:10.1016/j.scitotenv.2008.05.043)
25. Campos I, Vale C, Abrantes N, Keizer JJ, Pereira P. 2015 Effects of wildfire on mercury mobilisation in eucalypt and pine forests. *Catena* **131**, 149–159. (doi:10.1016/j.catena.2015.02.024)
26. Hoefen TM, Kokaly RF, Martin DA, Rochester C, Plumlee GS, Mendez G, Reichard EG, Fisher RN. 2009 *Sample collection of ash and burned soils from the October 2007 southern California Wildfires*. U.S. Geological Survey Open-File Report 2009–1038.
27. Plumlee GS, Morman SA, Meeker GP, Hoefen TM, Hageman PL, Wolf RE. 2013 The environmental and medical geochemistry of potentially hazardous materials produced by disasters. In *Treatise on geochemistry*, 2nd edn (ed. BSL Lollar), pp. 257–304. Oxford, UK: Elsevier.

28. Hibbert AR. 1967 Forest treatment effects on water yield. In *Forest hydrology* (eds WE Sopper, HW Lull), pp. 527–543. Oxford, UK: Pergamon.
29. Hibbert AR, Davis EA, Knipe OD. 1982 Water yield changes resulting from treatment of Arizona chaparral. In *Proc. of the Int. Symp. on the Dynamics and Management of Mediterranean Type Ecosystems, 22–26 June 1981, San Diego, CA, USA* (eds CE Conrad, WC Oechel), pp. 382–389. General Technical Report PSW-58, Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.
30. Bosch JM, Hewlett JD. 1982 A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydro*. **55**, 3–23. (doi:10.1016/0022-1694(82)90117-2)
31. Ebel BA, Hinckley ES, Martin DA. 2012 Soil-water dynamics and unsaturated storage during snowmelt following wildfire. *Hydro. Earth Syst. Sci*. **16**, 1401–1417. (doi:10.5194/hess-16-1401-2012)
32. Kinoshita AM, Hogue TS. 2015 Increased dry season water yield in burned watersheds in Southern California. *Environ. Res. Lett*. **10**, 014003. (doi:10.1088/1748-9326/10/1/014003)
33. Davies GM *et al.* 2016 The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. *Phil. Trans. R. Soc. B* **371**, 20150342. (doi:10.1098/rstb.2015.0342)
34. Gazzard R, McMorrow J, Aylen J. 2016 Wildfire policy and management in England: an evolving response from Fire and Rescue Services, forestry and cross-sector groups. *Phil. Trans. R. Soc. B* **371**, 20150341. (doi:10.1098/rstb.2015.0341)
35. Morris BL, Lawrence ARL, Chilton PJC, Adams B, Calow RC, Klinck BA. 2003 *Groundwater and its* susceptibility to degradation: a global assessment of the problem and options for ma*nagement*. Early Warning and Assessment Report Series, RS. 03-3. Nairobi, Kenya: United Nations Environment Programme.
36. Mansilha C, Carvalho A, Guimarães P, Espinha Marques J. 2014 Water quality concerns due to forest fires: Polycyclic Aromatic Hydrocarbons (PAH) contamination of groundwater from mountain areas. *J. Toxicol. Environ. Health Part A* **77**, 806–815. (doi:10.1080/15287394.2014.909301)
37. Bladon KD, Emelko MB, Silins U, Stone M. 2014 Wildfire and the future of water supply. *Environ. Sci. Tech*. **48**, 8936–8943. (doi:10.1021/es500130g)
38. Moody JA, Shakesby RA, Robichaud PR, Cannon SH, Martin DA. 2013 Current research issues related to post-wildfire runoff and erosion processes. *Earth-Sci. Rev*. **122**, 10–37. (doi:10.1016/j.earscirev.2013.03.004)
39. Nyman P, Sheridan GJ, Jones OD, Lane PNJ. 2011 Erosion and risk to water resources in the context of fire and rainfall regimes. In *Proc. of Bushfire CRC and AFAC 2010 Conf. Science Day, 1 September 2011, Sydney, Australia* (ed. RP Thornton), pp. 170–181. Boca Raton, FL: CRC.
40. Shakesby RA, Moody JA, Martin DA, Robichaud PR. 2016 Synthesizing empirical results to improve predictions of post-wildfire runoff and erosion response. *Internat. J. Wildland Fire* **25**, 257–261. (doi:10.1071/WF16021)
41. Neary DG, Ryan KC, DeBano LF (eds). 2005 *(rev. 2008) Wildland fire in ecosystems: effects of fire on soils and water*. General Technical Report RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station.
42. Shakesby RA, Doerr SH. 2006 Wildfire as a hydrological and geomorphological agent. *Earth-Sci. Rev*. **74**, 269–307. (doi:10.1016/j.earscirev.2005.10.006)
43. Olivella MA, Ribalta TG, de Febrer AR, Mollet JM, de las Heras FXC. 2006 Distribution of polycyclic aromatic hydrocarbons in riverine waters after Mediterranean forest fires. *Sci. Total Environ*. **355**, 156–166. (doi:10.1016/j.scitotenv.2005.02.033)
44. Vila-Escalé M, Vegas-Vilarrúbia T, Prat N. 2007 Release of polycyclic aromatic compounds into a Mediterranean creek (Catalonia, NE Spain) after a forest fire. *Water Res*. **41**, 2171–2179. (doi:10.1016/j.watres.2006.07.029)
45. Rhoades CC, Entwistle D, Butler D. 2011 The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado. *Int. J. Wildland Fire* **20**, 430–442. (doi:10.1071/WF09086)
46. Audry S, Akerman A, Riotte J, Oliva P, Maréchal J-C, Fraysse F, Pokrovsky OS, Braun J-J. 2014 Contribution of forest fire ash and plant litter decay on stream dissolved composition in a sub-humid tropical watershed (Mule Hole, Southern India). *Chem. Geol*. **372**, 144–161. (doi:10.1016/j.chemgeo.2014.02.016)
47. Murphy SF, Writer JH, McCleskey RB, Martin DA. 2015 The role of precipitation type, intensity, and spatial distribution in source water quality after wildfire. *Environ. Res. Lett*. **10**, 084007. (doi:10.1088/1748-9326/10/8/084007)
48. Desilets SLE, Nijssen B, Ekwurzel B, Ferré TPA. 2007 Post-wildfire changes in suspended sediment rating curves: Sabino Canyon, Arizona. *Hydrol. Process*. **21**, 1413–1423. (doi:10.1002/hyp.6352)
49. Reale JK, Van Horn DJ, Condon KED, Dahm CN. 2015 The effects of catastrophic wildfire on water quality along a river continuum. *Freshwater Sci*. **34**, 1426–1442. (doi:10.1086/684001)
50. Mast MA, Murphy SF, Clow DW, Penn CA, Sexstone GA. 2015 Water-quality response to a high-elevation wildfire in the Colorado Front Range. *Hydrol. Process*. (doi:10.1002/hyp.10755)
51. Martin YE, Johnson EA, Gallaway JM, Chaikina O. 2011 Negligible soil erosion in a burned mountain watershed, Canadian Rockies: field and modelling investigations considering the role of duff. *Earth Surf. Process. Landforms* **36**, 2097–2113. (doi:10.1002/esp.2236)
52. Shakesby RA, Wallbrink PJ, Doerr SH, English PM, Chafer CJ, Humphreys GS, Blake WH, Tomkins KM. 2007 Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forest assessed in a global context. *For. Ecol. Manag*. **238**, 347–364. (doi:10.1016/j.foreco.2006.10.029)
53. Cerdà A, Doerr SH. 2010 The effect of ant mounds on overland flow and soil erodibility following a wildfire in eastern Spain. *Ecohydrology* **3**, 392–401. (doi:10.1002/eco.147)
54. Gallaway JM, Martin YE, Johnson EA. 2009 Sediment transport due to tree root throw: integrating tree population dynamics, wildfire and geomorphic response. *Earth Surf. Process. Landforms* **34**, 1255–1269. (doi:10.1002/esp.1813)
55. Moody JA, Martin DA. 2001 Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surf. Process. Landforms* **26**, 1049–1070. (doi:10.1002/esp.253)
56. Jackson M, Roering JJ. 2009 Post-fire geomorphic response in steep, forested landscapes: Oregon Coast Range, USA. *Q. Sci. Rev*. **28**, 1131–1146. (doi:10.1016/j.quascirev.2008.05.003)
57. Moody JA, Martin DA. 2009 Forest fire effects on geomorphic processes. In *Fire effects on soils and restoration strategies* (eds A Cerdá, P Robichaud), pp. 41–79. Enfield, NH: Science Publishers.
58. Moody JA. 2001 Sediment transport regimes after a wildfire in steep mountainous terrain. In *Proc. of the Seventh Federal Interagency Sedimentation Conf., 25–29 March 2001, Reno, NV, USA*, pp. X-41–X-48. Washington, DC: Subcommittee on Sedimentation, Federal Inter-agency Committee on Water Resources.
59. Emelko MB, Silins U, Bladon KD, Stone M. 2011 Implications of land disturbance on drinking water treatability in a changing climate: demonstrating the need for ‘source water supply and protection’ strategies. *Water Res*. **45**, 461–472. (doi:10.1016/j.watres.2010.08.051)
60. Gleason KE, Nolin AW, Roth TR. 2013 Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. *Geophys. Res. Lett*. **40**, 4654–4661. (doi:10.1002/grl.50896)
61. Miller K, Yates D. 2006 *Climate change and water resources: a primer for municipal water providers*. Denver, CO: AWWA Research Foundation and the University Corporation for Atmospheric Research.
62. Santín C, Doerr SH, Otero XL, Chafer CJ. 2015 Quantity, composition and water contamination potential of ash produced under different wildfire severities. *Environ. Res*. **142**, 297–308. (doi:10.1016/j.envres.2015.06.041)
63. Lehner B *et al.* 2011 High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management. *Front. Ecol. Environ*. **9**, 494–502. (doi:10.1890/100125)
64. Moody JA, Martin DA. 2004 Wildfire impacts on reservoir sedimentation in the western United States. In *Proc. of the Ninth Int. Symp. on River Sedimentation, Yichang, China*, pp. 1095–1102. Beijing, People’s Republic of China: Tsinghua University Press.
65. Meixner T, Wohlgemuth P. 2004 Wildfire impacts on water quality. *Southwest Hydrol*. **3**, 24–25.
66. Khan SJ, Deere D, Leusch FDL, Humpage A, Jenkins M, Cunliffe D. 2015 Extreme weather events: should

drinking water quality management systems adapt to changing risk profiles? *Water Res*. **85**, 124–136. (doi:10.1016/j.watres.2015.08.018)

67. Eamus D, Hatton T, Cook P, Colvin C. 2006 *Ecohydrology: vegetation function, water and resource management*. Collingwood, Australia: CSIRO Publishing.
68. Brookes J *et al.* 2008 *A practical guide to reservoir management*. Research Report 67. Water Quality Research Australia.
69. Strange EM, Lane DR, Herrick CN. 2009 *Utility guidance for mitigating catastrophic vegetation change in watersheds*. Denver, CO: Water Research Foundation.
70. Glaves DJ, Morecroft M, Fitzgibbon C, Lepitt P, Owen M, Phillips S. 2013 Natural England Review of Upland Evidence 2012—The effects of managed burning on upland peatland biodiversity, carbon and water. Natural England Evidence Review, Number 004.
71. Holden J, Chapman PJ, Palmer SM, Kay P, Grayson R. 2012 The impacts of prescribed moorland burning on water colour and dissolved organic carbon: a critical synthesis. *J. Environ. Manag*. **101**, 92–103. (doi:10.1016/j.jenvman.2012.02.002)
72. Clay GD, Worrall F, Fraser EDG. 2009 Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog. *J. Hydrol*. **367**, 41–51. (doi:10.1016/j.jhydrol.2008.12.022)
73. Rockström J *et al.* 2014 *Water resilience for human prosperity*. Cambridge, UK: Cambridge University Press.
74. Lenton TM. 2013 Environmental tipping points. *Annu. Rev. Environ. Res*. **38**, 1–29. (doi:10.1146/annurev-environ-102511-084654)
75. Guiterman CH, Margolis EQ, Swetnam TW. 2015 Dendroecological methods for reconstructing high-severity fire in pine-oak forests. *Tree-Ring Res*. **71**, 67–77. (doi:10.3959/1536-1098-71.2.67)
76. Robinne F-N, Miller C, Parisien M-A, Emelko MB, Bladon KD, Silins U, Flannigan M. 2016 A global index for mapping the exposure of water resources to wildfire. *Forests* **7**, 16. (doi:10.3390/f7010022)
77. United Nations Economic Commission for Europe. 2009 *Guidance on water and adaptation to climate change*. Geneva, Switzerland: United Nations.
78. Chang SE, Shinozuka M. 2004 Measuring improvements in the disaster resilience of communities. *Earthquake Spectra* **20**, 739–755. (doi:10.1193/1.1775796)
79. McCarthy PD. 2012 Climate change adaptation for people and nature: a case study from the U.S Southwest. *Adv. Clim. Change Res*. **3**, 22–37. (doi:10.3724/SP.J.1248.2012.00022)
80. Thaler T, Griffith G, Gilliam N. 2014 A community based approach to improving resilience of forests and water resources: a local and regional climate adaptation methodology. In *Forest conservation and management in the Anthropocene, Conf. Proc.* (eds VA Sample, RP Bixler), pp. 361–378. RMRS-P-71. Fort Collins, CO: US Department of Agriculture, Forest Service. Rocky Mountain Research Station.
81. Emelko M, Sham CH. 2014 *Wildfire impacts on water supplies and the potential for mitigation: Workshop Report*. Canadian Water Network and Water Research Foundation.
82. Postel S. 1992 *The last oasis: facing water scarcity*, 3rd edn. London, UK: Earthscan.
83. Gleick P. 1993 *Water in crisis: a guide to the world's fresh water resources*. New York, NY: Oxford University Press.
84. Falkenmark M, Folke C. 2003 Freshwater and welfare fragility: syndromes, vulnerabilities and challenges. *Phil. Trans. R. Soc. Lond. B* **358**, 1917–1920. (doi:10.1098/rstb.2003.1413)
85. United Nations World Water Assessment Programme (WWAP). 2015 *The United Nations World Water Development Report 2015: Water for a Sustainable World*. Paris: UNESCO.
86. Dudley N, Stolton S (eds). 2003 *Running pure: the importance of forest protected areas to drinking water*. Gland, Switzerland: World Bank/WWF Alliance for Forest Conservation and Sustainable Use.
87. Weidner E, Todd A. 2011 *From the forest to the faucet: Drinking water and forests in the U.S., Methods Paper*. Washington, DC: USDA Forest Service.
88. Brown TC, Froemke P. 2012 Nationwide assessment of nonpoint source threats to water quality. *BioScience* **62**, 136–146. (doi:10.1525/bio.2012.62.2.7)
89. Scott J, Helmbrecht D, Thompson MP, Calkin DE, Marcille K. 2012 Probabilistic assessment of wildfire hazard and municipal watershed exposure. *Nat. Hazards* **64**, 707–728. (doi:10.1007/s11069-012-0265-7)
90. Bowman DMJS, O'Brien JA, Goldammer JG. 2013 Pyrogeography and the global quest for sustainable fire management. *Annu. Rev. Environ. Resour*. **38**, 57–80. (doi:10.1146/annurev-environ-082212-134049)
91. Krawchuk MA, Moritz MA. 2014 Burning issues: statistical analyses of global fire data to inform assessments of environmental change. *Environmetrics* **25**, 472–481. (doi:10.1002/env.2287)
92. Falkenmark M, Gottschalk L, Lundqvist J, Wouters P. 2004 Towards integrated catchment management: increasing the dialogue between scientists, policy-makers and stakeholders. *Internat. J. Water Resour. Devel*. **20**, 297–309. (doi:10.1080/0790062042000248619)
93. Oki T, Kanae S. 2006 Global hydrological cycles and world water resources. *Science* **313**, 1068–1072. (doi:10.1126/science.1128845)
94. Falkenmark M. 1977 Water and mankind: a complex system of mutual interaction. *Ambio* **6**, 3–9.
95. Bondar YI, Navumau AD, Nikitin AN, Brown J, Dowdall M. 2014 Model assessment of additional contamination of water bodies as a result of wildfires in the Chernobyl exclusion zone. *J. Environ. Radioactivity* **138**, 170–176. (doi:10.1016/j.jenvrad.2014.08.018)
96. Thom D, Seidl R. 2015 Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biol. Rev*. (doi:10.1111/brv.12193)