Current Forestry Reports
https://doi.org/10.1007/s40725-019-00099-y

FIRE SCIENCE AND MANAGEMENT (ME ALEXANDER, SECTION EDITOR)

Global Wildland Fire Management Research Needs

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Abstract

Purpose of Review This review is on global wildland fire management research needs from the standpoint of "integrated fire management". It seeks to apply a characterisation of fires to frame research needs, and also recognise some differences in research needs between "normal wildfires" and "extreme wildfire events" and draw some distinctions between the needs for developing and developed countries.

Recent Findings In the past, the dominant approach to fires in developed countries has been to suppress them including prohibition of fire use. In developing countries, the approach has tended to be similar. However, fires are a landscape problem in both developed and developing contexts, not resulting from insufficient or inadequate means of suppression, but from fuel continuity and accumulation. The impacts of fires are becoming higher profile, due to sizes and intensity in part but also from land use and demographic changes and their interactions, which see more people, more assets and ecological and economic values affected and publicised. Not fully appreciating the ecological role, impact, social, cultural and economic context in which fires are occurring, and the contributing factors and underlying causes of the fire problem, has seen planning, policy, development and other influences, alter landscapes and made populations increasingly vulnerable. Key to successfully integrating ecology, society and fire management technologies is effective analysis of the situation. This requires strengthened focus, including through use of social science and related disciplines. Damaging fires suggest that suppression alone is not sufficient to deal with wildfire, with the damage and loss that results in some cases being catastrophic. The implications of the limits of suppression need to be a component for planning risk reduction, readiness, response and of research. Similarly, comprehensive analyses and figures for damage and losses, including suppression costs, would have implications for wildland fire planning and investment. Existing research findings need to be applied and further research undertaken as necessary.

Summary Application to wildland fire management globally of existing research, and further research as needed, is required to analyse, select appropriate strategies, and apply management, monitor implementation and enable continuous improvement to reduce vulnerability and underpin resilience. This approach is termed "integrated fire management" and is particularly valuable for developing countries. For them, there may be the potential to reduce or avoid the wildfire damage and loss trends experienced in developed countries, through development and application of what has already been researched and operationalised in other contexts.

Keywords Integrated fire management · Fire research · Fire review · Landscape · Developing countries

Introduction

Wildfires combine combustion, vegetation, topography and weather conditions across space and time, including long-term climate and weather from the past. Fire science research has made significant progress in modelling, predicting and improving understanding of management of planned fires and also of wildfires, and providing support for fire managers who have responsibility for them. Understanding of fire as an ecological force in the landscape is providing insight so that fire managers can consider the role of fires more fully [1–3]. The improvements in computing power and related technology has enabled further refinement of models and use of diverse and expanded data sets [4].

This review on "global wildland research needs for integrated fire management" has been prepared from the

This article is part of the Topical Collection on *Fire Management*

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Published online: 18 December 2019

standpoint of integrated fire management rather than research. This perspective is not that of fire science, which is the work of researchers usually undertaken in specialty units, universities and institutions. This review is intended to identify existing knowledge and indicate areas of research required around ecological, social, cultural and economic aspects of fire, and models and tools, that can be used to improve integrated fire management. It takes the approach of:

1. Setting out a context for fire management and briefly describing wildfire trends
2. Identifying global level sources of guidance that inform global wildland fire management and research
3. Assessing and characterising "fire research" undertaken in the past to consider its origins and drivers
4. Describing the wildland fire management research needs globally by applying a fire characterisation
5. Considering these inputs to characterise "global wildland research needs for integrated fire management"

Fire Context

Fires have been used by humans for millennia and play a role in many ecosystems. The use of fire for hunting, favouring preferred plants for food or fibre, clearing for agriculture and grazing, easing travel and controlling pests is well documented, historical and continues today [5]. Fires contribute to the maintenance of some ecosystems, such as savannas, and less frequent fires in temperate and boreal ecosystems contribute to a mosaic of habitats that are of varying ages and stages of regeneration. More fire or less fire in an ecosystem may change species mix, structure and biodiversity [2, 5]. Between 2003 and 2012, approximately 67 million hectares of forest burned annually across the globe [6]. The impact of climate trends on fires is complex and variable across ecosystems, geographies and time, but the projections are predominantly for increased fire risk [7, 8].

Wildfires continue to have significant impacts globally, with lives being lost, built assets, forests, land production and productivity being threatened, landscapes being degraded and livelihoods disrupted. Damaging fire events in the past decade have been associated with heat waves and droughts [9•] and include the following: Greece, 2007 and 2018; Australia, 2009; Russia, 2010; USA, 2013, 2017 and 2018; Canada, 2016; Chile, 2017; and Portugal, 2003, 2005 and 2017.

A review of large wildfire events between 2002 and 2013 [9•] identified that:

- Wildfires can have disastrous impacts and extreme wildfire events can be "disasters", usually in relation to human assets and impacts on people.
- Wildfires reported as being economically or socially disastrous are concentrated in suburban areas intermixed with flammable forest in the developed world.
- Wildfire events are globally distributed and are associated with dangerous fire weather conditions, will continue to occur and are inevitable features of flammable biomes.
- The authors suggest that regional land use changes can substantially reduce the occurrence of wildfire disasters.
- Nearly all (96%) of the disastrous extreme wildfire events were associated with fire dangerous meteorological conditions such as high winds, temperatures, or fire danger, or climatic conditions such as drought or abundant antecedent precipitation in arid regions.
- The pivotal role of meteorological conditions in driving extreme wildfire events signals increasing global vulnerability to these events with climate change.

Analyses of fires indicate that ~90% of fires are readily contained and burn 10% or less of the total area burnt. This suggests that for those fires the current planning, management and technologies are working well in restricting the number of fires that do escape containment to less than 10%. The suppression that is being aligned and mobilised is suitable to most of the situations that are being encountered, though that is not to say that improvements cannot be made or value added. The other ~90% of the area burnt is by ~5–10% of fires [10–12]. These events are the ones that gain profile, such as Greece and California in July 2018, and include loss of life, damage and loss to property, infrastructure and environmental impacts. These wildfires are uncontainable as they exceed the limits of suppression. There is nothing that fire fighters can do to stop or contain such wildfires until weather or fuel conditions change [13, 14].

People are the cause of the majority of fires globally through a combination of limited access to alternative approaches to fire, accidents, weak understanding of fire risk, machinery, poor practice, negligence and carelessness. In the FAO coordinated Global Fire Assessment 2006 [15], several regions estimated the proportion of fires that were human caused: Mediterranean 95%, South Asia 90%, South America 85%, Northeast Asia 80% and the Balkans 59%. Over the past two decades, the potential for local people, communities and traditional fire knowledge to contribute to a risk reduction in severe wildfires, damage and loss from severe wildfires was recognised and applied in some cases [16].

The trend of rural to city migration, socioeconomic and policy changes has resulted in fewer people, less activity and altered management in rural areas in developed countries [13, 17]. This trend has also been recognised in developing countries, though not as strongly. Globally, 6 out of every 10 people in the world are expected to reside in urban areas by 2030 with nearly all of this growth in Africa, Asia, Latin America and the Caribbean [18]. The land area covered by cities is predicted to triple as the urban population of developing countries doubles.

In the absence of effective urban planning, the consequences of this rapid urbanisation will be dramatic, potentially including for wildfire impacts. UN Habitat notes, "Urban law remains a highly segmented and complex field driven by a dynamic where technical objectives in specific fields are considered in isolation from each other as well as from the institutional, financial and social factors that will determine effectiveness" [18]. This includes planning for wildfires. Developing countries need to benefit from the knowledge, experience and research that has already taken place on wildland fires and the Wildland Urban Interface (WUI), as they transition from predominantly rural populations to increasingly urban dwelling people.

Fire Trends

The future of wildland fire, agreed among scientists, fire managers and fire agencies, is for increasingly difficult fire weather conditions, extended fire seasons and larger fires [19••]. Canada, with the history, data, expertise and interest available to do so has reviewed and analysed wildland fire into the future, providing a structured presentation of the potential for Canada. The review suggests that burned area may increase by 100% in the period to 2100 and fire numbers increase by 75% [20]. Climate change is suggested to be increasing the duration and changing the starting and finishing times of fire seasons and influencing fire extent, intensity and impacts [10].

Agency, government and media reports and the public view of wildfires tends to emphasise the visible damage and loss. The readily available data focuses on damage to human assets and firefighting costs but does not typically cover death and injury, health impacts or reduction in ecosystem services [21••].

Direct impacts are captured in developed countries (asset loss, lives, firefighting costs), but collection of indirect costs (injuries, health impacts, indirect and downstream economic losses/impacts, and ecosystem impacts such as water quality and degradation) are less common.

The expansion of the WUI, in particular, leads to increased risk, increased complexity of management, higher costs and increased damage and loss [19••, 22••]. In its recent occasional paper, IUFRO noted that:

- WUI is a global issue presenting in Argentina, Australia, Chile, France, Greece, Portugal, South Africa, Spain and the USA.
- There were 286,000 houses within wildfire perimeters in 2010, compared with 177,000 in 1990.
- Over 1600 houses were destroyed in 2017 in Chile, and more than 2500 homes in the Fort McMurray fire in Canada in 2016 with estimates of direct and indirect costs over US$7.5 billion, and in Knysna, South Africa, 1200 structures were destroyed or damaged during the June 2017 wildfire.
- Estimated losses due to catastrophic fires in the European Union during the period 2000–2017 accounted for 63.3B EUR (~$94B USD).

In the summer of 2015, large parts of Indonesia burned with an estimated $16.1B USD in losses and damage, roughly equivalent to 1.9% of the country's GDP [23]. The damage and loss experienced by people and impacts on landscapes and businesses can be enormous, with the loss of wood and timber values representing major costs as well.

Fire suppression in developed countries can also be very costly and is increasing. Stocks and Martell identified that for Canada overall, the fixed (presuppression) costs and the variable costs of suppression have been increasing since 1970 and become more variable [24]. They noted that fire management expenditure had risen from CA$290 million in the early 1970s to over CA$900 million in 2013. Over the last decade, annual wildfire suppression costs on US federal lands exceeded US$1.7 billion and US$1 billion in Canada.

The maximum fireline intensity for working directly on the flames is generally considered to be ~4000 kW/m. For indirect attack, where the tactic is to work at a distance from the wildfire, the limit of suppression is ~10,000 kW/m [13, 25–27]. Extreme wildfire events always exceed these limits. For example, the Pedrógão Grande wildfire that occurred in Portugal in June 2017, burned with fireline intensities from 20,000 to 60,000 kW/m and a rate of spread of 65 m/min (~4 km/h) [28••]. There will always be some wildfires that exceed the capacity for suppression. This is further complicated as society and demographics change, the landscape alters and the influences of climate change increase wildfire potential. Fire managers are now also confronted by political challenges, such as wildfire threats to public and firefighter health, smoke and greenhouse gas emissions [29].

Beyond the Limits of Suppression—Extreme Wildfire Events

There are many terms used to describe or label fires and they vary depending on the landscape being burned (forest, savanna, brush, scrub), the fuel type being burned (forest, chaparral, grassland), the social or cultural context (livelihoods, festivals, traditional, conflict) and perhaps regulatory framework (permit fires, illegal fires). The terms include fires, wildfires, wildland fire, forest fire, grass fire, scrub fire, brush fire, bush fire, veldt fire, rural fire, vegetation fire and so on [19••].

Fire science research requirements differ depending on the nature of the fires. Severe fire events in places where there are assets at risk need social/planning/human response research to reduce the risks of fatalities and losses as in some parts of the "developed" nations at present. The bulk of fire events need to be "under management", something that can involve one or all of the following: the science of fire danger rating, fuels and fire behaviour; the analysis and adaptation into application of approaches (procedures, systems, agency structures, roles and responsibilities, clarity of function) that have been demonstrated to already work in an existing context; and research on human and social dimensions to understand and to enable effective risk reduction that does not compromise livelihoods or long-term objectives and have unintended outcomes.

There is a significant amount of existing research, soundly based practice and emerging research. The range, impacts and changes in fires and by fires are varied, complex and large as described earlier. In an attempt to characterise the fire research that is needed, a characterisation of fires is useful and has been proposed by Tedim et al. [28••].

The "megafire" phenomenon was described by Williams et al. [30] based on a review of case studies of very large fire events. These fires tended to be of very large size, but their profile was raised and reinforced by their suppression difficulty, complexity and sometimes duration, and also in deep, sometimes long-lasting social, economic and environmental impacts. Bowman et al. [9•] noted the lack of a definition for "mega fires" when analysing what they termed "extreme wildfire events". They applied a process to MODIS data to classify fire radiative power events of 10 km by 10 km (10,000 ha) and identified the top 500 events between 2002 and 2013. These extreme wildfire events were then confirmed and classified by reference to independent data and media reports of home losses and disaster declarations into 144 "disaster" wildfires, an average of 13 per year over the period, and 334 "non-disaster" wildfires [9•].

Tedim et al. [28••] noted these approaches in developing a seven-level categorisation of fire events, with categories 5, 6 and 7 identified as "extreme wildfire events". This work recognised the need for "objective measurable parameters" for extreme wildfire events, in order to clarify the responses to them by policy makers, fire managers and researchers. Extreme wildfire events needed to be separated from the majority of fires that do little or no damage or are contained using existing capacities. The categorisation sets out the factors of extreme behaviour and the limits of suppression forms the boundary between "normal" fires and "extreme wildfire events". The environmental, social and economic impacts are recognised in the paper but not included in the categorisation as they are dependent on the landscape, its use and the vulnerability to wildfires. The relationship between wildfire size and impacts is "a complex and non-linear relation" and has led to their exclusion, so focus is on the descriptors of fires; fireline intensity, rate of (forward[1]) spread, spotting activity and spotting distance, and observable atmospheric phenomena of the formulation of pyro-cumulonimbus clouds and presence of downdrafts.

For an extreme wildfire event to be of interest or concern the adverse social impacts must be significant, and Tedim et al. [28••] note and agree with the separation by Bowman et al. [9•] of an extreme wildfire event from a disaster. The latter is defined by its impacts on human, ecological and economic facets. Interestingly, they specifically identify psychological impacts arising from the trauma of disasters that can endure for years post the event as a research need. Their preliminary proposal for a classification is set out in Table 1.

This characterisation provides a means to link research ideas and plans to needs allocated on the basis of the types of fires that are experienced or of most interest. Having fire reporting and recording is required to enable the fire history and trends of an area of interest (district, province or nation) to be reviewed and analysed so that the fire management and planning is informed, appropriate and research is relevant to the fire types, and targeted to need.

The Blueprint for Wildland Fire Science in Canada (2019–2029) [20] lists research priorities, many of which have been noted previously. That list of 23 topic areas under 6 pillars spans the full suite of needs for both normal and extreme wildfire events.

Integrated Fire Management

What constitutes good practice in fire management has been well documented [25, 31–35]. However, this is mainly focused on descriptions of needs, requirements and approaches for Readiness to fight fires and Response—firefighting. There are also a number of reference books on fire management, including those of Gill et al. [36], Chandler et al. [37], Scott et al. [38] and Leblon and Alexander [39] that present the thinking and approach to the full suite of fire management topics and were prepared by researchers but also managers. Notably, they reflect mainly national perspectives and the work of developed countries.

Often the messages conveyed to decision-makers and the public through the coverage of very dramatic and damaging severe wildfires encourage them to the view that firefighting is the main solution to harmful wildland fires, and so they react to short-term recurring crises. This presents a very simple picture of a complex situation that is in contrast to what is needed, which is focusing resources on long-term and sustainable solutions, by integrating fire management into land management and the routines of planning and operations. This requirement has been identified and described in a number of contexts [e.g., 38–40]. The proposition is made that damage and loss from wildfires has significant social and political aspects, including

[1] The term used is ROS, assumed to mean the forward rate of spread of the fire front.

Table 1 Seven-level categorisation of fire events (after Tedim et al. 2018)

Fire category	Fireline intensity (kW/m)	Rate of spread (m/min)	Flame length (m)	Spotting activity	Spotting distance (m)	Type of fire and capacity of control
Normal fires						
1	< 500	< 5 forest/shrub < 15 grassland	< 1.5	Absent	0	Surface fire Fairly easy
2	500–2000	< 15 forest/shrub < 30 grassland	< 2.5	Low	< 100	Surface fire Moderately difficult
3	2000–4000	< 20 forest < 50 shrub/grass	2.5–3.5	High	≤ 100	Surface fire, torching possible Very difficult
4	4000–10,000	< 50 forest < 100 shrub/grass	3.5–10	Prolific	500–1000	Surface fire, crowning likely depending on vegetation type and stand structure Extremely difficult
Extreme wildfire events						
5	10,000–30,000	< 150 forest < 250 shrub/grass	10–50	Prolific	> 1000	Crown fire, either wind- or plume-driven; spotting plays a relevant role in fire growth; possible fire breaching across n extended obstacle to local spread; chaotic and unpredictable fire spread Virtually impossible
6	30,000–100,000	< 300	50–100	Massive spotting	> 2000	Plume-driven, highly turbulent fire; chaotic and unpredictable fire spread; spotting, including long distance, plays a relevant role in fire growth; possible fire breaching across an extended obstacle to local spread Impossible
7	> 100,000 (possible)	> 300 (possible)	> 100 (possible)	Massive spotting	> 5000	Plume-driven, highly turbulent fire; area-wide ignition and firestorm development; non-organised flame fronts because of extreme turbulence/vorticity; and massive spotting Impossible

a lack of commitment to risk reduction across landscapes, rather than being beyond scientific understanding [39].

To date, inadequate attention has been paid to addressing underlying causes of fires and to preventing a damaging pattern of recurrent fire and degradation in burnt areas [41, 42]. The nexus of land management and economic, public and environmental pressures is an area for ongoing research that crosses disciplines.

There is a need to "integrate" socio-cultural realities and ecological imperatives into the landscapes where fire occurs. Integrated fire management (IFM) is a term developed for this intention [5, 17] which began to be used in the 1980s though its origin and provenance are not clear. The German Technical Cooperation Agency - Gesellschaft für Technische Zusammenarbeit (GTZ) (now GIZ) commenced the "Integrated Forest Fire Management (IFFM)" project in East Kalimantan in 1994, one of the earlier references to the term [43]. In an internal workshop held by GIZ in May 2000, IFM was described as focusing "… on flexible, pragmatic approaches designed to support local people's role in resource management. Specifically it entails the application of the art and science of modern wildland fire technologies and practices to the local fire problem – the community level" [44].

The focus of this review is on global wildland fire management research needs for IFM; the work of land and forest agencies and communities, which was set down as being: "All activities required for the protection of burnable forest and other vegetation values from fire and the use of fire to meet land management goals and objectives. It involves the strategic integration of such factors as a knowledge of fire regimes, probable fire effects, values-at-risk, level of forest protection required, cost of fire-related activities, and prescribed fire technology into multiple-use planning, decision making, and day-to-day activities to accomplish stated resource management objectives. Successful fire management depends on effective fire prevention, detection, and presuppression, having an adequate fire suppression capability, and consideration of fire ecology relationships" [45].

The descriptions used for IFM over time have evolved, but include a set of ideas and elements in common to those reflected in Wingard [44], and also by Myers [5], Sande Silva et al. [17], Rego et al. [46, 47] and by The Nature Conservancy [48]. The listing of elements overlaps and in summary includes:

- People

– the activities and the capabilities of rural populations in their work, use and occupation of the landscape (communities, individual land users)
– considering all types of "agents" from rural inhabitants (active in fire use and not) to fire management professional staff

- Fire in the landscape

– applying a holistic approach to addressing fire issues
– natural or human-caused wildfires within prescription and/or planned application of fire
– considering all fire types from beneficial to damaging
– consideration of fire ecology

- Activities

– all activities required for the protection of forest and other vegetation values from fire
– all activities associated with the management of fire prone land, including the use of fire to meet land management goals and objectives
– the different components of fire management; fire prevention, detection, suppression
– fire management systems such as planning and operational systems
– objectives of minimising the damage and maximising the benefits of fire
– a combination of prevention and suppression strategies and techniques

This definition touches on all the points listed but perhaps lacks a scalar indication—the local level. The intent is clear; consider all things together in context, a task best tackled at local level by communities.

Community-Based Fire Management Traditional Fire Knowledge

At the local community level is where the fires are ignited (by people mainly), fires escape containment, but fires can be initially attacked most effectively. This is also the level at which the fire context is best considered, ecology included, fire regimes known, and fire use and the balance of impacts can be effectively combined. The potential complexity has been, and continues to be, understood and applied at the local level by communities [16, 49, 50]. This is the initial level of "integration" at the local scale, and community-based fire management (CBFiM) is a valuable building block as a base upon which IFM can be articulated and then promoted up into jurisdictions at district, state/provincial and national levels.

The value and potential contribution of local people, communities and Traditional Fire Knowledge (TFK) has had significant attention, with initial framing of it in 2000 [51] and an international conference on the topic in 2002 [52]. CBFiM continues having a profile in the international sphere through the International Wildland Fire Conferences, and initiatives such as The Nature Conservancy's knowledge networks and FAO's development of case studies and a review [53, 54].

There are many elements of CBFiM and TFK, and they are combined and refined over time and between places so the area of interest is difficult to describe succinctly. Some authors have sought to describe the "knowledge systems" [50] and frame them to support analysis, further research and application [50, 55]. Approaches for systematic framing of CBFiM and TFK include considering them as pre-industrial and post-industrial anthropogenic fire regimes and by their current status: robust, declining, rejuvenating or historical (no longer practiced).

The fire knowledge involved can be, and usually is, sophisticated and based on long-term exposure and observations of weather, climate, vegetation, ecology, animals and wildlife, landscape, human needs, risks and benefits. Efforts to document, characterise and analyse CBFiM and TFK continue, and the value of it has been described [e.g., 16, 50]. The feasibility of adapting local processes from one context to others has been evaluated and is being trialled [56]. This will further the potential of reinvigorating, or implementing, CBFiM/TFK as has been done in Northern Australia [57].

A Fire Management Framework

In its Fire Management Strategy, FAO noted that globally wildfire is not being effectively brought under management and is compromising ecosystems, human lives, built assets and infrastructure, livelihoods and food security. Fires continue to affect landscapes and local people and create large volumes of greenhouse gases. Wildfires are upsetting the balance between natural fires that stimulate and sustain ecological processes, traditional fire use and community fire use.

Integrated approaches to fire management, as noted earlier, place greater emphasis on addressing underlying causes and seek long-term, sustainable solutions. To do that, it is necessary to consider fire and its management in a systematic way. There is no one size or approach that "fits all" to managing harmful forest fires and fire risks to people and ecosystems. Each situation has its own ecological, social, economic and political circumstances that need to be evaluated, understood, monitored, and mitigated or lived with. Effective and efficient fire management is built on past learning and requires the engagement of a wide variety of concerned stakeholders.

Such efforts can be framed and implemented systematically and consistently by considering five essential elements (the five Rs) that are the same as the globally adopted characterisation used in dealing with disasters and their management:

1. REVIEW—Analysis of the fire issue and identification of options for positive change
2. RISK REDUCTION—Prevention—focusing resources on the underlying causes of fires
3. READINESS—Preparing to fight fires
4. RESPONSE—Ensuring appropriate responses to unwanted damaging fires
5. RECOVERY—Community welfare, repairing infrastructure and restoration of fire-damaged landscapes

This fire management framework (Table 2) was developed in response to the need to have a process to "integrate" fire management [49].

Global Level Guidance

The strong emergence of Disaster Risk Reduction at global level has seen the Sendai Framework for Disaster Risk Reduction 2015–2030 [58] developed as the successor instrument to the Hyogo Framework for Action (HFA) 2005–2015: Building the Resilience of Nations and Communities to Disasters. The Sendai Framework has a strong emphasis on disaster risk management (before) as opposed to disaster management (during and after). Disaster risk reduction has also been broadened to both natural and man-made hazards.

The Sendai Framework articulates the following that should be considered in the context of wildfires: the need for improved understanding of disaster risk in all its dimensions of exposure, vulnerability and hazard; preparedness to "Build Back Better" (improved post-fire landscape management and use); and recognition of stakeholders and their roles and strengthening of international cooperation and global partnership.

Seven global targets have been agreed, and national targets and indicators will contribute to the achievement of the outcome and goal of the present framework. Managing wildfires better will contribute to a reduction in the following targets and indicators of the Sendai Framework:

- Global disaster mortality by 2030
- The number of affected people globally by 2030
- Direct disaster economic loss in relation to global gross domestic product
- Disaster damage to critical infrastructure and disruption of basic services

Focused action within and across sectors was identified in priority areas, the first of which was "understanding disaster risk", which for wildfires is a critical shortfall in many countries.

An FAO thematic study presented information on fire incidence, impact and management [15]. A summary of the fire area affected annually lists 229 countries and territories of which 83 have no data, meaning not zero fires but that no fire data was provided or able to be obtained. This includes places such as the Holy See, San Marino, Channel and Faroe Islands, Bahamas, Cayman Islands, Nauru and the Falkland Islands, for whom wildland fires are not likely an issue and may not occur. It appeared that 54 places supplied recent data, suggesting that the remainder, 92 countries or territories, provided old data or averages. Overall, 175 of 229 reports had weak or no data on fire incidence or land area burned [15]. Notably, in the study, there was specific identification of the critical requirement to enhance technology transfer of skill, knowledge, ideas, know-how and technology from developed to developing countries. Research in how to understand how and why fire is used is required.

In relation to science and research, the Sendai Framework [58] notes the need to: promote and improve dialogue and cooperation among scientific and technological communities, other relevant stakeholders and policymakers; to enhance the scientific and technical work on disaster risk reduction; promote scientific research on disaster risk patterns, causes and effects; and identify research and technology gaps and set recommendations for research.

The Sendai Framework is being linked to, and worked on, in the context of the Sustainable Development goals (SDGs). They were formalised in a resolution adopted by the UN General Assembly on 25 September 2015 - Transforming our world: the 2030 Agenda for Sustainable Development [59]. The 17 SDGs and 169 targets included sought to build on the Millennium Development Goals and are considered to be "integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental". They are to stimulate and guide action over the next 15 years [59].

Fire management plays an important role in realising Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss [60]. Challenges and concerns were explored during the International Wildland Fire Conference held in Pyeongchang, Republic of Korea, in 2015, with the following having implications for wildland fire management research:

- Increasing impacts of climate change on climate variability, weather patterns, fuels and fire behaviour, particularly the lengthening of fire seasons, the size in area burned, and the extremity and frequency of fire occurrences

Table 2 The fire management framework—"Fire on a Page" (After Moore et al 49)

Examples of System Tools	System Process Components	
• Maps (vegetation, topography, tenure, assets, roads, ignition distribution etc.) • Fire behaviour prediction tools • Spatial databases • Demographic information • Cultural & Social Context of fire • Ecological response to fire (fire histories, fire effects information, fire regimes)	**REVIEW - ANALYSIS OF THE FIRE PROBLEM** **1. Fire Likelihood** **Ignition history** **2. Consequence** of **Fire** on **Assets** ⬇ Economic, Social, Environmental ⬇ Intensity, Spread Rate, Duration ⬇ Value, Vulnerability **3. Ecological context of fire**	System
• Fire use laws/regulations, enforcement • Planning controls • Education programs • Fire behaviour guides, ignition & control resources, planning & reporting tools. • Firebreak construction guides • Building construction codes • Ecological fire training • Fire use education	**RISK REDUCTION - PREVENTION** **1. Ignition Reduction Strategies** - Regulate fire use, educate fire users, technology improvements, development planning controls **2. Impact Mitigation Strategies** - Fuel reduction (e.g., by burning, grazing & other means) - Reduce asset vulnerability (e.g. construction standards) - Establish/maintain containment features (e.g. fuel breaks) **3. Fire Use Strategies** - Ecosystem maintenance - Fire regime restoration	Improvement
• Climate, weather monitoring & prediction • Fire Danger Rating system. • FDR public notification means. • Detection/suppression needs assessment. • Fire detection, suppression & communications resources. • Fire training systems and tools	**READINESS - PREPAREDNESS TO FIGHT FIRES** **1. Strategies** - Early Warning/Predictive systems - Community warning mechanisms - Detection and response infrastructure - Communications systems - Mobilisation & co-ordination plans - Response triggers and levels - Competent fire control staff	Monitoring
• Response mobilisation plans • Operational responsibilities & procedures. • Strategic information access tools • Decision support tools • Operational management systems	**RESPONSE - FIRE FIGHTING OPERATIONS** **1. Detection and Reporting** **2. First Response** **3. Containment and Control** **4. Mop Up and Patrol** **5. Command and Control**	& Review
• Damage assessment tools • Recovery assistance plans	**RECOVERY POST FIRE** **1. Community welfare assistance** **2. Economic loss reduction (e.g., salvage logging and replanting, infrastructure repair)** **3. Environmental repair**	

- Impacts of smoke on human health and air quality as well as fire-induced professional and civilian injuries and fatalities
- Impacts of fires from land-use change and agricultural/industrial clearing
- Increasing impacts of wildfires at the interface with rural settlements and urban fringes
- Impacts of socio-economic and demographic changes, including consequences of human migration, on fire regimes

Past Fire Research

The history of fire research is not a widely covered or analysed topic. In the USA, there have been reviews, such as the 50-year history of the Fire Research Laboratory at Missoula [61, 62], and a report on the Gisborne era of forest fire research [63]. Similarly in Canada, periodically the research "system" has taken stock [64–67]. In 2018, Canada published a "Blueprint for Wildland Fire Science" [20] in response to the review of the Canadian Wildland Fire Strategy [68], based on an assessment of future needs to meet the anticipated wildfire challenges. There is a lack of other similar reviews outside North America. Where described, fire research work, effort and its elevation to major programmes, centres and funding has been in response to a fire problem, recognised as such by key actors, catalytic individuals and agencies with public interest.

Fire research has tended to be driven at a national level. Plans that have been prepared and collaborations formed include the Canadian Wildland Fire Strategy 2016 [68] and the subsequent blueprint for wildland fire science [20], National Fire Plan Research and Development Application in the United States [69] and the Joint Fire Science Program [70], Bushfire and Natural Hazards Cooperative Research Centre of Australia [71], its predecessor the Bushfire Cooperative Research Centre, and the FIRE PARADOX Project of the European Union [17]. International collaborations occur as opportunity and scientific contacts permit, such as the work on the Indonesian and Malaysian fire danger ratings systems undertaken by national researchers with support from Canada and Canadian researchers [71].

Review of some FAO and other international fire management publications identified some research interests and proposals through time that provide a view of what has been undertaken or proposed. Show and Clarke [31] set down the core components and requirements for readiness to fight fires and responding to them with some framework factors of planning, organisation and administration. The research requirements noted were to support the technical services required, with the objective being "to find out how to prevent fires from starting, how to put out a fire, once started, while it is still small". They noted requirements for research that included:

- Collection and analysis of statistics
- Prevention, including public education
- Fire behaviour
- Fire control
- Economics, particularly the evaluation of the effects of fire.

The proceedings of a seminar on forest fire prevention and control [32] noted some research elements, including the preparation of a directory of research institutes, calling the attention of IUFRO and national research institutes to the need for research into silviculture and forest fire behaviour and danger rating, impact of fire on forest ecosystems, mapping fire risks, models for fire danger rating prediction and fire behaviour. They also noted an interest in knowing more of the "motivation and attitudes of people who cause wildfires".

Following on from earlier work on wildland fire research needs by Barney [99], an experienced fire manager and a fire researcher conducted a survey of fire managers from US federal and state wildland fire protection agencies in 1988 [73]. The results framed up the concerns at that time, most of which were related to fire suppression. Those aspects that had a potential research component or input included the following: coping with information and data flow; the changing fire problem at the wildland-urban interface; updating fire detection systems; improved weather forecasting and needs for new or improved fire behaviour and fire danger models.

They also noted, presciently, "Many important fire suppression problems have their roots in organizations, policies and budgets rather than in lack of knowledge of suppression techniques and practices". Today, this observation remains valid with the additional complications of the vegetation, fire ecology, planning and social responses to fire hazards at the urban interface that have emerged more strongly since 1988.

The proceedings of a fire policy meeting held in Rome in 1998 looked at the principles, policy and process of involving stakeholders in systematic fire management, and also included other land use management [74]. The specific topics centred around procedures, institutional cooperation and collaboration, and disseminating knowledge. Research was not included as a topic and barely mentioned, other than being noted as requiring strengthening and highlighting three topics: the development of space borne remote sensing for fire detection, early warning and decision support; post-fire recovery techniques and ecosystem recovery processes; and the impact of climate change on fire regimes and fire severity.

The relative decline of fire research in South Africa was noted and there was also identification of some research needs; for example, fire research generally in Mozambique, prescribed burning and burned area mapping in Namibia (East

Caprivi), plus fire danger rating system, fuel assessment, impact assessments and development of burning prescription guidelines in Philippines, and fire behaviour in Finland, among others [74].

Following the extensive fire season of 1997–1998 in Indonesia, fire research was stimulated in that country and region and involved use of remote sensing, social research into land use and fire use, economic analyses, non-fire land use conversion, and recommendations for a national action plan in research and technology development and increasing international research cooperation [74–76].

The Expert Consultation on Global Forest Resources Assessment 2000 held in 1996 recommended that FAO provide annual statistics/estimates for each country on the number of forest fires and the area burned over the period 1990–2000 [77]. In the regional reports then prepared there is reference to research, in the form of summarised results and ideas and options for implementation into management. Fire research was identified as being mainly absent with some exceptions.

The 2000 Global Assessment noted: "In reviewing the global fire situation, it is apparent that a continued emphasis on the emergency response side of the wildfire problem will only result in future large and damaging fires. The way out of the emergency response dilemma is to couple emergency preparedness and response programmes with more sustainable land use policies and practices. Only when sustainable land use practices and emergency preparedness measures complement each other do long-term natural resource benefits accrue for society" [77].

The follow-up FAO Global Review 2006 [15] did not report on research specifically, but research was noted in some of the regional reports. Research was being done in some countries, but the results were not always shared and the lack of adequate and continuing finance was noted as a limitation. The need for international cooperation in fire research was noted in a number of reports. The need for specific research into the use of remote sensing for fire detection, along with carbon pools and flows affected by fire and the impact of fire on permafrost, were also mentioned.

The FAO Fire Management Voluntary Guidelines did note the importance of science and technology, albeit briefly [33]. The guidelines identify that fire science is multidisciplinary and interdisciplinary, with integration across the various fields of fire research being critical. The guidelines noted the need for "… transfer of scientific knowledge" through vocational education and public education emphasising appropriate language for communities to understand and absorb, including translation into local languages. Particularly in Principle 11, where knowledge transfer was identified, appropriate application of knowledge was highlighted as being essential in all fire management activities, including but not limited to, engaging in quality scientific research for the creation of new knowledge; collecting traditional, local knowledge and using that knowledge in appropriate aspects of the fire management programme; translating scientific, research and technical materials and making them accessible, at the appropriate technical level, to local managers, firefighters and communities. The importance of converting analysis and research into fire management and operations was also identified in the review of the delivery of Joint Fire Science Program projects [71] and also noted in the Sendai Framework [58]. Clark [69] noted the achievements of the USDA Forest Service national fire plan research projects particularly in four key areas of firefighting capacity, rehabilitation and restoration, hazardous fuel reduction and community assistance.

Wildland Research Needs

The fire research that has been formulated and planned is almost exclusively found in countries with developed economies, and stable and diverse research capacity (via agencies, universities, the private sector and individuals). The need for fire research was clearly identified, and accepted by and supported by government. In the USA, the early development of the US Forest Service included response to the 1910 fires [78] and the evolution of the 10 am Policy that led to investment in fire science research in support of policy. In Canada and Australia, there was similarly a response to severe fire seasons and significant losses [79–82] that also saw an increased focus on fire science.

Evolution in research capacity has occurred in Mediterranean countries, Turkey, Greece, Italy, France, Spain and Portugal; in temperate and boreal forests of China and the Russian Federation; with capacity in South Africa emphasising fire ecology [2, 83]. Countries with high forest cover that is not fire adapted, such as the Amazon and Congo Basin and Indonesia, did not have a fire problem to address until land use change expanded at larger scales [41, 84–86]. To date, the Congo Basin countries tend to be less affected by fires [15]. Many other countries have not yet developed fire research capacity as a formalised or structured response to need. As the influence of demographic change, economic development and climate change are expressed, they may need to include consideration of fire research. Should that requirement emerge, then the transfer and adaptation of existing knowledge and research from other countries will be needed, as noted in the Sendai Framework [58].

The need to understand why fires are lit or occur, and the need to understand the dynamics of land use, planning, emergency response and management, community resilience and reactions to fire events by populations, has seen strengthened interest and emphasis on social science and related disciplines. This need applies globally in both developed and developing countries. McCaffery [87] reviewed the state of knowledge and noted consistent trends in how people respond to fire across various geographies, including some research in Australia outside the USA where most previous work had been conducted [88]. Researchers involved in the Bushfire and Natural Hazards Cooperative Research Centre in Australia are also working on social aspects including teaching and education, hazard communications, decision making, mental health and intercultural collaboration [72, 89–91].

There has been research undertaken on the limits of suppression [e.g., 26, 92, 93] that confirms the efforts of people, tools and machines in direct attack at their maximum are orders of magnitude below the energy release rates of extreme wildfire events. This research could be extended following a comprehensive review of what is known on the topic [94, 95]. Importantly, the implications of the limits of suppression need to be a component of planning for risk reduction, readiness and response. Some recent fires, and many of the past, indicate quite clearly that suppression, while containing 90% of wildfires or more, is not sufficient for all fires and the damage and loss that results can be catastrophic.

There are also economic analyses and figures for damage and loss assessment provided for many severe wildfire events [e.g., 93, 96]. While they generate figures and provide some indication of damage and loss, it is not clear there is a consistent or comprehensive agreed methodology applied [97]. Full damage and loss assessment, including the suppression costs and opportunity costs and other economic metrics, if clear, would have implications for wildland fire prioritisation and investment. These would include:

- Assessment of the returns on investment of funding risk reduction
- Stimulus to framing insurance options for damage and loss, a form of risk reduction
- Base information for cost-benefit analysis of investment and expenditure on readiness and response in terms of damage and loss, avoided damage and loss
- Basis for assessing value for money in the effectiveness, efficiency and impact of fire response including allocating resources only when they will have impact and standing them down when they will not

This is a fraught area of research to describe, as the paradigm in developed countries has emphasised suppression. This has contributed to the well-entrenched assumptions that the increasingly high levels of investment and expenditure on firefighting are both necessary and making a critical difference to the outcomes of severe wildfire events.

Framing Fire Research Needs for IFM

The application of the characterisation of fires [28••] and the fire management framework to global fire research needs as reflected earlier can be set out in a table (Table 3).

Table 3 Table of global wildland fire research needs

	Both "normal" fires and EWEs	Extreme wildfire events
Review and analysis	• Numbers of fires • Fire sizes • Geographic location • Mapping • Spatial databases • Demographic information • Cultural and social context of fire • Ecological response to fire (fire histories, fire effects information, fire regimes) • Increasing impacts of climate change on climate variability • Collection and analysis of fire data	• Research of underlying factors, situation and context to strengthen understanding of these complex events
Risk reduction	• Incidence of large/damaging fires • Impacts of fires from land-use change and clearing • Impacts of socio-economic and demographic change • Public education • Risk analysis • Fire cause modelling and research	• Wildland urban interface • Returns on investment of funding risk reduction • Stimulus to framing insurance options for damage and loss
Readiness	• Fire behaviour prediction and fire danger rating	• Fire behaviour prediction and fire danger rating
Response	• Fire behaviour and fire danger rating • Fire suppression effectiveness and thresholds • Risk communication	• Assessing value for money in the effectiveness, efficiency and impact of fire response
Recovery	• Damage and loss assessment, including indirect costs and opportunity loss	• Impacts of smoke • Psychological impacts arising from disasters

Research needs for fires identified under the characterisation as "Normal" [28••] can be considered in two contexts.

1. The application of existing research methods, results and the adaptation of products and tools where they have not been applied, and
2. The improvement by research of existing understanding, products and tools

The first is generally the case for countries that have not had an obvious or recognised fire "problem", something that is the case for many developing countries. The second relates to countries that have a recognised problem with fires and efforts to understand, plan, manage and undertake research have been made and are ongoing.

The table allocates research topics noted in this review by aligning them to the five Rs and listing them in columns for normal fires, extreme wildfire events or noting where the research is applicable to both fire types. Listing research needs using the fire management framework may also help to prioritise the elements of the framework that are most needed or where the effort will be most beneficial.

Within the Limits of Suppression—"Normal Fires" (Mainly Developing Countries)

Developing countries, to a large extent, experience "normal fires" and rarely report or record extreme wildfire events. It is likely that all the research listed in Table 3 will in time probably be required for developing countries.

In developing countries with fire management issue(s) to address or that are emerging, "pure research" may not be what is required. Developing countries will likely benefit initially from the adaptation and application of existing fire science along with the procedures and processes for generating it, while also ensuring that the research is relevant to the national context and contributing data, information and insights that are useful and can be transferred into operations and practice.

The overwhelming need in developing countries is to understand their fire management "problem" and its context. For that to be done, the need is for review, data collection and analysis, informed by past research methods and means, but being operational or management-focused on the application of available fire science and not new fire science "research". Systematic review of current data and information, the appropriate analysis of it and then, based on the findings, the adaptation and application of insights about fires from elsewhere, are needed.

An example is the adaptation into application of the fire danger rating that is readily communicated to people and fire users, summarises seasonal conditions of dryness, fuel availability and fire likelihood related to locally observed characteristics [e.g., 98].

Understanding the sources, causes and motivations for starting fires is a critical aspect in developing countries, those with emerging economies, and potentially developed countries as well. For developing countries, fire management research resources need to be redirected to support fire data collection and analysis, and perhaps research, which improves understanding of fire causes, identifies existing management practices that encourage harmful fires, and promotion of management systems that take advantage of well-established fire use.

To do this, the studies and analysis carried out by FAO for countries and other reviews [33, 74, 99] identified that among the initial "research" required is data collection and analysis of the fire context and situation. The potential means and inputs include:

- Maps (vegetation, topography, tenure, assets, roads, ignition distribution, etc.)
- Fire behaviour prediction tools
- Spatial databases
- Demographic information
- Cultural and social context of fire
- Ecological response to fire (fire histories, fire effects information, fire regimes)

The analysis of the existing data available, including remote sensing data for historical perspective if useful, would then help to confirm trends in:

- Numbers of fires
- Fire sizes
- Geographic location
- Incidence of large/damaging fires

This data enables the analysis of how and why fires are being started and being used.

Developing countries rarely report figures for damage and loss or different impacts [99]. Agricultural and livestock impacts can be significant and exceed the capacity of the community to deal with the wildfire or to recover from it without external support. Research into methodologies for damage and loss assessment is already conducted in some sectors in developed countries [99] and recognised as a requirement [20]. This is also needed for developing countries.

Beyond the Limits of Suppression—"Extreme Wildfire Events" (Mainly Developed Countries)

In developed countries, where there is a research sector the sector continues to address fires and their management. In general, the application of research to fire management needs (fire behaviour, fire danger, weather/fuel/fire interactions, fire ecology, cultural and social context of fire), and the products and tools that result has been put in place. The base exists and the research and resources continue to be refined. The emerging need is for extreme wildfire events.

Extreme wildfire events, to date, are mainly confined to developed countries where the concentration of assets and wildland fuels are close to each other and damage and losses result. The combinations and interactions of land use changes, demographic change, economic development and climate trends strongly influences the phenomena of biomass accumulation, due to altered management and leads to fuel increase and fuel continuity. The wildfires that result can become extreme events and directly impact people, assets and landscape values with high levels of damage and loss.

Research needs for extreme wildfire events should have a focus in supporting the framing, planning and resolution of them. Such fires have escaped, and containment will only be possible when the fire weather conditions and/or fuel availability change in ways that reduce fire behaviour to levels where response capacity can be effective. The emphasis of efforts generally, and research specifically, requires focus on risk reduction and the aspects of societal and human behaviour related to warnings, safety, evacuation, community resilience, decision making, and the aspects of structure protection and management of the WUI.

Conclusions

Key to successfully integrating ecological and societal factors and fire management technologies is effective analysis of the fire situation. What is the ecological role, impact, social, cultural and economic context in which fires are occurring? Who is starting fires and, most critically, why? What are the fuels in the area and how does fire behave in them? What are the contributing factors and underlying causes of the fire problem, such as land tenure issues, illegal logging, invasive species or climate change?

An approach is needed to systematically analyse the fire problem, identify the needs and select the appropriate strategies, planning tools and management to meet the requirements, monitor their implementation and enable continuous improvement, adaptation, reduce vulnerability and underpin resilience. This approach is IFM, and a tool to systematically work towards sustainable and sensible approaches to the management of fire is the fire management framework based on the five Rs. Characterising fires in a way that can be applied readily and across geographies and landscapes is also very useful in separating out research needs and relating them to fires as experienced and which are of concern.

The dominant approach to fires in the history of developed countries has been to suppress them and undertake prohibition of fire use. In developing countries, the tendency is to adopt the same approach. However, fires are a landscape problem. They are not a problem resulting from insufficient or inadequate means of suppression, but from the situation of fuel continuity and accumulation of fuels from vegetation, characteristics of land occupation, and traditional and current fire use. Altered landscapes have made the population increasingly vulnerable. The pressures and influences that lead to the contributing factors for wildfire disasters being in place need to be analysed, articulated and clearly described for solutions to be found.

The research areas listed against the fire management framework reach beyond the traditional actors, institutions and stakeholders interested in or involved in wildland fire management research. The complexity now being faced by fire and land managers, communities and disaster response agencies and systems includes the WUI, influences of climate change and increasing costs, damage and losses. The expanded realm of sectors and interests will include indigenous communities more clearly and actively, communities and local people, the health sector, planners, owners and users of critical infrastructure, insurers, the broader emergency response sector and decision-makers, particularly those that decide the allocation of investment and financial flows. They will need to be integrated into research for IFM.

During the process of considering the disastrous wildfires in Portugal and Europe of 2017, one fire manager stated:

I don't want more resources, I want a better landscape.[2]

The need expressed, by this manager and others, is for IFM at the landscape scale to more effectively address the pressures and influences that lead to wildfire disasters. Global wildland research for IFM should also be focused in support of efforts at the landscape scale.

Acknowledgements The author wishes to thank the organisations and projects he has worked on during his career to date that provided the experience and exposure to be able to prepare this paper, the FAO for enabling the work and Dr. Martin Alexander for the invitation to contribute it. Colleagues that were important to the clarification of the "5Rs" framework are acknowledged, Paul de Mar who framed it up and Brett Shields who also contributed to its refinement. The viewpoints expressed here have benefited from innumerable discussions over many years with colleagues in developing countries and fire research for which I thank them, including Hartmut Abberger, David Bowman, Phil Cheney, Stuart Christie, Helmut Dotzauer, Bill de Groot, Alexander Held, Anja Hoffmann, Matt Jolly, Mwangi Kinyanjui, Harry Luke, Francesco Rego, Ross Smith, Cathelijne Stoof and Domingos Xavier Viegas among many.

Compliance with Ethical Standards

Conflict of Interest Dr. Peter F. Moore declares that he has no conflicts of interest.

Human and Animal Rights and Informed Consent This article contains no studies with human or animal subjects performed by the author.

[2] Attributed to Marc Castellnou, a strategic analyst with the fire service in Catalunya, Spain.

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