Diverse knowledge informing fire policy and biodiversity conservation

Policy Brief

KEY POINTS

- There is a need to reassess fire policy following the increase in severe wildfires over the last decade in many countries that has led to rising costs and damage to lives, property and natural resources.
- Fire policies often aim to suppress wildfires in attempts to reduce effects on ecosystems and societies despite evidence that these efforts increase fire risk in the future; increasingly, policy includes the use of controlled fires to reduce the intensity of future catastrophic events.
- In many regions, fire is perceived as an unnatural process. However, evidence from long-term ecological records show that fire is a natural part of most ecosystems and that many livelihoods and cultures are intrinsically connected to fire as a process.
- Long-term ecological data can identify the natural and cultural legacies on present landscapes, including knowledge on fire and vegetation changes in response to past climate and land use.
- Knowledge about traditional fire use by local and Indigenous communities can provide information on culturally and environmentally sustainable fire management practices to improve biodiversity and local livelihoods.
- Used together, the diverse knowledge from science and local communities can help fire management practices meet conservation targets (e.g. biodiversity, ecosystem resilience), mitigate negative impacts of wildfires (e.g. health effects, loss of life and property), and engage in efforts of respectful reconciliation with Indigenous and Descendant groups.
- We recommend that these diverse forms of knowledge (long-term ecological data and traditional knowledge) are incorporated into the evidence base to support decisions on fire policy in areas that will be most affected by future climatic and land-use changes.

PAGES PAST GLOBAL CHANGES

GLOBAL PALEOFIRE WORKING GROUP 2

ROYAL HOLLOWAY UNIVERSITY OF LONDON

QRA Quaternary Research Association

cnrs CHRONO ENVIRONNEMENT

1 Fire is a global issue

There has been an increase in catastrophic wildfires around the world, such as in Portugal (2017), Greece (2018), Australia (2019) and Brazil (2019). Severe fires have important consequences on people's livelihoods, human health, climate change and ecosystem services (including forest products, biodiversity, water and soil quality). The rising economic and social costs of fire, particularly in the transition between unoccupied land and urban areas (the wildland-urban interface), makes it a priority issue for ecosystem managers and policy makers around the world[1,2].

1.1 Wildfires are controlled by different factors

Wildfires are controlled by a combination of climatic, land-use, and vegetation factors which vary across regions[3]. In boreal forests, wildfires occur during warmer conditions in summer[3,4]. In the drier tropical savannas, fires depend on the length of the dry season and fuel availability[5]. In general, fires are more common under "intermediate climates", meaning that conditions are neither too dry to limit fuel accumulation, nor too wet to reduce flammability[6,7]. Examples of such intermediate conditions are found in tropical savannas or in mixed evergreen-deciduous forests. Due to accelerated human intervention over recent decades, fires have occurred under a wider range of climate conditions that would historically be less conducive to large-magnitude wildfires. For example, land use and deforestation are responsible for higher burning in the wet tropics, as shown by satellite data in the Amazon and in Southeast Asia[8].

1.2 Fire is a natural ecosystem process

Fire is often viewed as a damaging factor, yet diverse lines of evidence clearly show it is a fundamental ecological process in nearly all ecosystems[9,10]. Many plants evolved over millions of years to depend on fire and thrive in its presence[10,11]. For example, in western US forests the lodgepole pine requires fire to germinate, and the ponderosa pine is adapted to high frequency, low intensity fires. Fire-adapted species play an important role in ecosystems, as they can recover quicker after fire[12]. Such ecological benefits are seen in many environments today and show that fire supports important features of landscapes including biodiversity, forest structure and nutrient cycling[3,12,13].

Figure 1. The effects of catastrophic fires (like the Yellowstone fires of 1988) can still be seen in landscapes after several decades (Photo credit: DC).

1.3 Fire and its benefit to people

Many local community livelihoods and cultures depend and benefit from fire[14]. For example, fire maintains many ecosystem services, including food resources and forest biomass. Fire plays a critical role in subsistence agriculture where small areas of forest, typically of one hectare in size, are cut and burned as part of rotational farming[15]. In pastoral systems, fire is used to produce fresh feed for livestock, particularly in seasonal climates where the dry season reduces the nutrient quality of grasses. In addition, fire is used to protect certain habitats and resources (such as fruiting

Figure 2. Fire is a natural ecological process and many tree species, like the ponderosa pine, are adapted to fire (Photo credit: DC).

trees), for gathering, to maintain sacred sites, to clear travel routes, and to maintain cultural and spiritual connections with the landscape[16]. There is a long-history of fire-human interactions in most continents[17]; however, fire is still perceived as "unnatural" in many regions, and its key role for people is often undermined[14].

1.4 Fire management approaches vary widely around the globe

Fire management around the world ranges from fire suppression and exclusion to actively using fire as a management tool[1,18]. Fire suppression has been common in Venezuela where wildfires are a regular occurrence, and only approximately 13% of total fires can be combatted[15,19]. An example of active management is prescribed burning, which is widely used in North America to reduce fuel accumulation and the likelihood of severe fires[20]. In southern Europe, fire regulations are implemented at the national level, resulting in different management strategies across countries. For example, prescribed burning is adopted in many Mediterranean countries to mitigate the effects of fuel accumulation resulting from land abandonment[1,18]; this same management practice instead is generally not allowed in Greece[18]. In many cases, fire policies such as fire suppression have fostered the idea that fire is "unnatural" and "bad," thus not considering the beneficial effects for the environment and people over time.

Figure 3. A traditional winter fire in montane grasslands in the Pyrenees (Photo credit: CC).

Figure 4. An experimental fire in Kansas (US) to assess the effects of changing burning intensities and frequencies on prairie's species (Photo credit: DC).

1.5 Fire challenges in a future warmer world

Fire management approaches are challenged by uncertainties related to future climate changes[21]. It is not easy to accurately predict the future occurrence of fire, because climate conditions and fuel availability will change across regions. In temperate and boreal regions, warmer and drier conditions will cause more forest fires[22]. Many arid regions will experience more rainfall, fuel build-up and burning[5,21]. Additional insights can be gained by considering the history of fires during past climatic conditions (**Box-1**). Future fires will also depend on societal and land use changes. Land abandonment in rural areas is causing forest regrowth and an increase in fire, as seen in many Mediterranean countries[1,23]. Conversely, the expansion of the wildland-urban interface is causing a reduction in fuel and consequently in area burned[24]. Therefore, future trends will largely differ across regions. Other factors include land conversion (e.g. palm oil in the tropics), political changes (changed investment in policies), and rapid loss of traditional fire knowledge[14]. There is a growing need for more sustainable approaches that adapt to future climate changes and mitigate the effects of catastrophic wildfires on natural resources and public health[1,25,26].

Box-1: The fire-climate relationship over millennia

In the past, fire and vegetation changed in response to variations in climate. Since the end of the Last Glacial Maximum (about 18,000 years ago) biomass burning increased globally due to rising temperatures and forest build-up[27,28]. In general, biomass burning was high when forest advanced during warm interglacial periods, and low during cold glacials when forests were reduced[29,30]. Past warm periods, such as those identified ca. 130,000 years ago, can be considered "analogues" for future conditions in a +2C degrees warmer world[31] and can inform us about fire regimes under "natural conditions" (i.e. when human influence on fire regimes was less relevant[32]). In addition to climate, fires in many regions of the world have been strongly modified by people for millennia[17,33]. Failure to account for the complex response of fire to many drivers (climate, vegetation, human impact) may hinder assessment of future ecosystem changes over the coming decades.

2 Informing fire policy and biodiversity conservation

Fire will be inevitable in most ecosystems and the complex mix of socio-economic and regional climate changes will require new strategies to increase the resilience of human and ecological communities to fire globally[25,34]. The inclusion into the decision-making of more diverse knowledge, such as traditional knowledge and long-term ecology, can improve our understanding of present fires and help set more realistic goals for fire management in future fire-prone ecosystems.

2.1 Traditional ecological knowledge informing sustainable management

Traditional ecological knowledge represents a rich source of information on how people manage their environment in sustainable and productive ways. In many regions, traditional burning activities maintain a landscape mosaic with a range of species habitats that enhance biodiversity and reduce the amount of flammable fuel, lowering the risk of uncontrolled fires[15,19]. Ecosystems are characterised by specific fire regimes in terms of frequency and intensity, and people have traditionally developed burning practices at different times of the year linked to livelihood activities. For example, in Kenya and Tanzania, fires set by Maasai pastoralists promote green growth for grazing animals[35]. In the 'conucos' (farm) cultivation practices by Pemon people in Venezuela, fire has beneficial effects on the nutrient-poor soils because it acts as a fertilizer, improving crop yields while maintaining nutrient rich soils[19]. In Indigenous rotational farming practices in Northern Australia, food plants are selectively promoted ("fire-stick farming"). Similarly, fire management by Yurok and Karuk tribes in the Pacific Northwest support traditional food production[36]. The loss of this traditional knowledge in recent times (as a result of historical processes of colonisation, resource extraction and state intervention), and rapidly changing socio-environmental conditions, along with fire exclusion policies, has led to significant alterations of fire regimes and the increased likelihood of more severe fires[14].

Figure 5. An example of traditional use of fire in South America for shifting cultivation in forests (Photo credit: BB)

2.2 Knowledge from the past informing present conservation and fire management

Long-term ecology can provide information on how past climates, fire and land use have shaped present landscapes, and how wildfire changed under natural or human-induced factors[3,17]. For example, changes in fire activity at the onset of agriculture in central Europe (ca. 5500 BC) show how forests have been cleared or managed for millennia; this legacy is visible in today's landscapes in the form of cultivars or other introduced species[37]. Long-term ecological information is particularly useful considering that the dynamics of many ecosystems operate on scales too long to be directly recorded by ecological monitoring[38,39]. For example, forests change on scales of decades to centuries in ways that are difficult to observe directly. Information from biological records such as tree rings, charcoal[40], fossil pollen in lakes, bogs and other natural archives can be used to address many conservation issues related to biodiversity losses[38], invasive species[41], and species distribution under future climates[31]. Importantly, these records can also help identify ecological legacies of Indigenous land use that are still represented in the composition and structure of modern vegetation communities. For example, in the Border Lakes Region of central North America, tree ring records have helped describe the linkages between Indigenous land use practices, fire, and forest structure[42].

2.3 Integrating diverse knowledge can provide unique insights

Accounting for the dynamic nature of fire over time, using long-term ecological knowledge and traditional knowledge to inform fire policy could help to:

a) Increase ecosystem resilience

Different species can show different responses to fire disturbances; for example, many are sensitive to fire, while others thrive with it. Long-term ecological data can help characterise which species are "fire sensitive" or "fire tolerant" and the rate of forest recovery after fire, complementing ecological monitoring[43]. Traditional knowledge can inform on which food species have been sustained by people through an active fire management[44]. The reintroduction or promotion of fire tolerant species in modern landscapes can improve ecosystem resilience, while in some cases provide livelihoods to sustain local communities.

b) Maximise biodiversity

Long-term ecology can reveal the natural and human-induced causes driving past biodiversity changes[44,45], and their legacies on present landscapes. Traditional knowledge complements this with information on the fire management practices that can maximize biodiversity and local livelihoods. Using participatory and ethical community engagement can help towards the application of culturally and environmentally appropriate practices[15,16].

c) Identify historical baselines

Long-term ecology provides baseline information on the variability of fire in ecosystems before modern land use practices[46]. For example, the identification of past fire baselines in Quebec[47,48] helped select alternative approaches to industrial forest management that best meet Canadian and Quebec policies[49]. In regions with a longer history of human impact (Africa, Europe), long-term ecology and traditional knowledge can reveal how traditional practices have adapted to past environmental changes, as documented in many arid or semi-arid environments over the last millennia[50]. Knowledge derived from this socio-ecological history can help guide future adaptations to expected rapid climate change.

d) Understand the effects of burning practices

Fire management policy in Australia, Brazil, Venezuela, Québec, Finland, Sweden, France, Spain is moving towards including controlled burning as a management approach. Nevertheless, the effects of such practices on ecosystems are often unknown or debated[1,51,52]. Past ecosystem history can show which fire regime is characteristic for a region[46] and how Indigenous burning practices affected fire occurrence in the past[42]. This information is key for assessing whether modern management practices such as prescribed burning should be adopted.

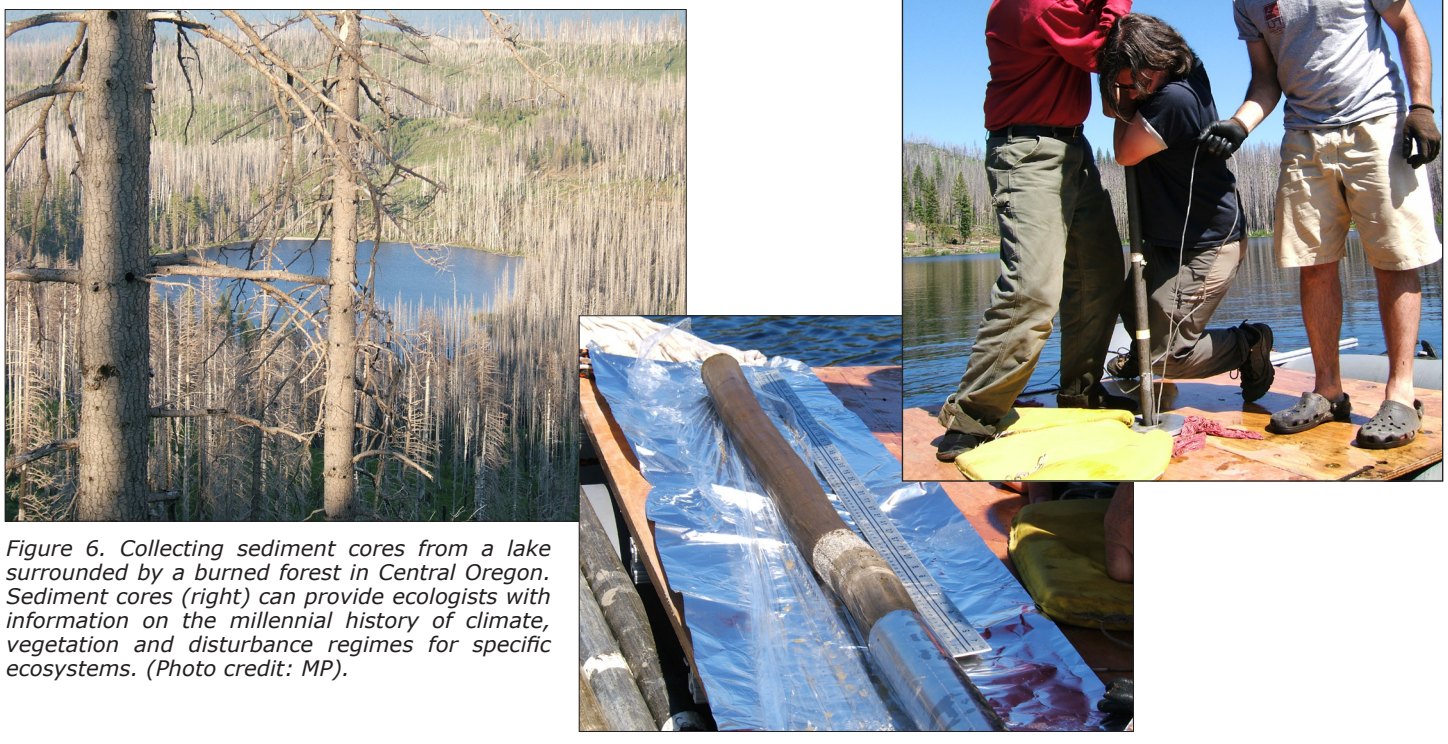

Figure 6. Collecting sediment cores from a lake surrounded by a burned forest in Central Oregon. Sediment cores (right) can provide ecologists with information on the millennial history of climate, vegetation and disturbance regimes for specific ecosystems. (Photo credit: MP).

3 Policy Recommendation

Fire management practices will be most effective if they are based on local and regional contexts. We therefore do not advocate a particular approach, but rather we recommend that fire management and policy incorporate long-term ecological and traditional knowledge in their evidence base to set locally- and regionally-relevant benchmarks for fire regimes and to identify targets related to biodiversity conservation and resilience in landscapes that are acceptable to local communities. These efforts can be achieved through the following steps:

1. Collect and integrate diverse knowledge

Use long-term ecological data to assess present fires in the context of the region's historical fire variability. For example, assess whether wildfires are outside of an "historical norm" compared to past conditions. Gather information on the social and ecological benefits of traditional fire management. Use systematic evaluation[53] of long-term ecological data and traditional knowledge to take into account all the available evidence.

2. Set fire management plans based on the diverse knowledge

Set benchmarks for fire regimes, in terms of frequency and intensity, that maximise biodiversity and reduce fire risks. Based on the information from long-term fire records[54], consider controlled burning in areas where fire has been artificially excluded, and monitor the outcomes. Prioritise traditional burning practices that focus on targeted species to preserve traditional food sources and other ethnobotanical resources.

3. Involve local communities in decision-making

Raise "public understanding" for fire by communicating potential risks and educating the public that fire is a natural component in many ecosystems. Promote the inclusion of traditional knowledge approaches that are collaborative, community-focused, and contribute to the continuation of cultural traditions, intergenerational knowledge transfer, and practical know-how[14]. Finally, encourage the participation of different stakeholders and local communities in a process of intercultural exchange.

4. Promote cultural and natural diversity

Maintain mosaic landscapes that prevent catastrophic fires and preserve both natural and cultural heritage values[37]. Replacing monocultures with traditional practices (e.g swidden agriculture, pastoralism) may increase ecosystem diversity and resilience while also achieving increased carbon sequestration targets.

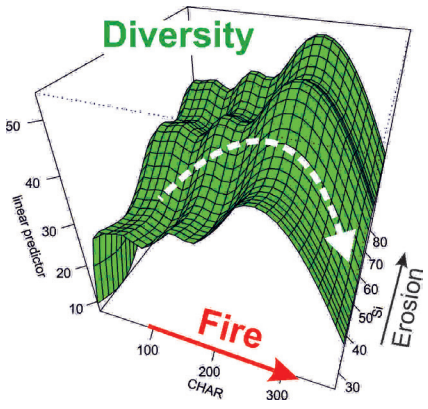

Figure 7. Knowledge from past environments can reveal the fire regime conditions that maximise biodiversity in specific ecosystems. In the Alps, plant biodiversity is maximised at intermediate conditions[45] and traditional fire practices can help maintaining the balance between natural and cultural heritage values. (Photo credit: DC).

Acknowledgements

This Policy Brief results from a workshop held at Royal Holloway University of London and funded by PAGES, the Quaternary Research Association (QRA), and Chrono-environnement CNRS/Université de Franche-Comté. The workshop gathered 30 international participants from 15 countries to discuss ongoing challenges on biodiversity conservation and fire policy at global scale. This initiative is promoted by the Global Paleofire Working Group (https://www.gpwg.paleofire.org/), a network of researchers promoting data collection and analyses of sedimentary charcoal records from around the world.

Contributors: Colombaroli D (RHUL), Mistry J (RHUL), Milner A (RHUL), Vannière B (CNRS, Université de Franche-Comté), Adolf C (U. of Oxford), Bilbao BA (Simón Bolívar U.), Carcaillet C (École Pratique des Hautes Études), Connor S (Australian National U.), Daniau AL (CNRS, U. of Bordeaux), Hawthorne D (U. of St Andrews), Jeffers E (U. of Oxford), Larson E (U. of Wisconsin-Platteville), Petrokofsky G (U. of Oxford), Power MJ (U. of Utah), Sinnadurai P (Brecon Beacons National Park Authority), Berrio JC (U. of Leicester), Cassino R (U. Federal de Ouro Preto), Gildeeva O (U. of Jena), Grosvenor M (King's College London), Hardiman M (U. of Portsmouth), Hennebelle A (U. de Montréal), Kuosmanen N (U. of Helsinki), Lestienne M (CNRS, Université de Franche-Comté), Portes MC (U. of Göttingen), Rockell G (Surrey Wildlife Trust), Tsakiridou M (U. of Portsmouth), Walsh A (RHUL).

Contact: Daniele Colombaroli, Centre for Quaternary Research (CQR), Department of Geography, Royal Holloway University of London (RHUL), Egham, Surrey TW20 0EX, UK. daniele.colombaroli@rhul.ac.uk

How to cite this document: Colombaroli D, Mistry J, Milner A, Vannière B, Adolf C, Bilbao BA, Carcaillet C, Connor S, Daniau AL, Hawthorne D, Jeffers E, Larson E, Petrokofsky G, Power MJ, Sinnadurai P, Berrio JC, Cassino R, Gildeeva O, Grosvenor M, Hardiman M, Hennebelle A, Kuosmanen N, Lestienne M, Portes MC, Rockell G, Tsakiridou M, Walsh A (2019). Diverse knowledge informing fire policy and biodiversity conservation. DiverseK Policy Brief. Royal Holloway University of London, UK.

Photo Cover: A fire set for smallholder agriculture in Guatemala (Photo credit: BV).

Graphic Design: M. Kelsey (RHUL).

Website: The Global Paleofire Working Group

Twitter: @diverse_k

References

1. Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, et al. Learning to coexist with wildfire. Nature. 2014;515(7525):58-66.
2. Prentice IC. The Burning Issue. Science. 2010;330(6011):1636-7.
3. Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, et al. Fire in the Earth System. Science. 2009;324(5926):481-4.
4. Kelly R, Chipman ML, Higuera PE, Stefanova I, Brubaker LB, Hu FS. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. Proceedings of the National Academy of Sciences of the United States of America. 2013;110(32):13055-60.
5. van der Werf GR, Randerson JT, Giglio L, Gobron N, Dolman AJ. Climate controls on the variability of fires in the tropics and subtropics. Global Biogeochemical Cycles. 2008;22(3).
6. Colombaroli D, Ssemmanda I, Gelorini V, Verschuren D. Contrasting long-term records of biomass burning in wet and dry savannas of equatorial East Africa. Global Change Biology. 2014;20(9):2903-14.
7. Marlon JR, Bartlein PJ, Carcaillet C, Gavin DG, Harrison SP, Higuera PE, et al. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience. 2008;1(10):697-702.
8. van der Werf GR, Randerson JT, Giglio L, van Leeuwen TT, Chen Y, Rogers BM, et al. Global fire emissions estimates during 1997-2016. Earth System Science Data. 2017;9(2):697-720.
9. Bond WJ. Fires in the Cenozoic: a late flowering of flammable ecosystems. Frontiers in Plant Science. 2015;5.
10. Pausas JG, Keeley JE, Schwilk DW. Flammability as an ecological and evolutionary driver. Journal of Ecology. 2017;105(2):289-97.
11. Scott AC. The Pre-Quaternary history of fire. Palaeogeography Palaeoclimatology Palaeoecology. 2000;164(1-4):281-329.
12. Donato DC, Fontaine JB, Robinson WD, Kauffman JB, Law BE. Vegetation response to a short interval between high-severity wildfires in a mixed-evergreen forest. Journal of Ecology. 2009;97(1):142-54.
13. McLauchlan KK, Higuera PE, Gavin DG, Perakis SS, Mack MC, Alexander H, et al. Reconstructing disturbances and their biogeochemical consequences over multiple timescales. BioScience. 2014;64(2):105-16.
14. Mistry J, Berardi A. Bridging indigenous and scientific knowledge. Science. 2016;352(6291):1274-5.
15. Mistry J, Bilbao BA, Berardi A. Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. Philosophical Transactions of the Royal Society B-Biological Sciences. 2016;371(1696).
16. Mistry J, Berardi A, Andrade V, Kraho T, Kraho P, Leonardos O. Indigenous fire management in the cerrado of Brazil: The case of the Kraho of Tocantins. Human Ecology. 2005;33(3):365-86.
17. Bowman DMJS, Balch J, Artaxo P, Bond WJ, Cochrane MA, D'Antonio CM, et al. The human dimension of fire regimes on Earth. Journal of Biogeography. 2011;38(12):2223-36.
18. Fernandes PM, Davies GM, Ascoli D, Fernandez C, Moreira F, Rigolot E, et al. Prescribed burning in southern Europe: developing fire management in a dynamic landscape. Frontiers in Ecology and the Environment. 2013;11:E4-E14.

19. Bilbao BA, Leal AV, Mendez CL. Indigenous Use of Fire and Forest Loss in Canaima National Park, Venezuela. Assessment of and Tools for Alternative Strategies of Fire Management in Pemón Indigenous Lands. Human Ecology. 2010;38(5):663-73.
20. Stephens SL, Ruth LW. Federal forest-fire policy in the United States. Ecological Applications. 2005;15(2):532-42.
21. IPCC. Intergovernmental Panel on Climate Change2013.
22. Hu FS, Higuera PE, Duffy P, Chipman ML, Rocha AV, Young AM, et al. Arctic tundra fires: natural variability and responses to climate change. Frontiers in Ecology and the Environment. 2015;13(7):369-77.
23. Pausas JG, Fernandez-Munoz S. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. Climatic Change. 2012;110(1-2):215-26.
24. Andela N, Morton DC, Giglio L, Chen Y, van der Werf GR, Kasibhatla PS, et al. A human-driven decline in global burned area. Science. 2017;356(6345):1356-61.
25. McWethy DB, Schoennagel T, Higuera PE, Krawchuk M, Harvey BJ, Metcalf EC, et al. Rethinking resilience to wildfire. Nature Sustainability. 2019;2(9):797-804.
26. McMorrow J, Cavan G, Walker J, Aylen J, Legg C, Quinn C, et al. Fire Interdisciplinary Research on Ecosystem Services (FIRES). Policy Brief. 2010.
27. Daniau A-L, Bartlein PJ, Harrison SP, Prentice IC, Brewer S, Friedlingstein P, et al. Predictability of biomass burning in response to climate changes. Global Biogeochemical Cycles. 2012;26.
28. Power MJ, Marlon J, Ortiz N, Bartlein PJ, Harrison SP, Mayle FE, et al. Changes in fire regimes since the last glacial maximum: An assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics. 2008;30(7-8):887-907.
29. Daniau AL, Harrison SP, Bartlein PJ. Fire regimes during the Last Glacial. Quaternary Science Reviews. 2010;29(21-22):2918-30.
30. Harrison SP, Goni MFS. Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. Quaternary Science Reviews. 2010;29(21-22):2957-80.
31. Fischer H, Meissner KJ, Mix AC, Abram NJ, Austermann J, Brovkin V, et al. Palaeoclimate constraints on the impact of 2 degrees C anthropogenic warming and beyond. Nature Geoscience. 2018;11(7):474-85.
32. Lawson IT, Tzedakis PC, Roucoux KH, Galanidou N. The anthropogenic influence on wildfire regimes: charcoal records from the Holocene and Last Interglacial at Ioannina, Greece. Journal of Biogeography. 2013;40(12):2324-34.
33. Vannière B, Blarquez O, Rius D, Doyen E, Brücher T, Colombaroli D, et al. 7000-year human legacy of elevation-dependent European fire regimes. Quaternary Science Reviews. 2016;132:206-12.
34. Gillson L, Whitlock C, Humphrey G. Resilience and fire management in the Anthropocene. Ecology and Society. 2019;24(3):14.
35. Butz RJ. Traditional fire management: historical fire regimes and land use change in pastoral East Africa. International Journal of Wildland Fire. 2009;18(4):442-50.
36. Marks-Block T, Lake FK, Curran LM. Effects of understory fire management treatments on California Hazelnut, an ecocultural resource of the Karuk and Yurok Indians in the Pacific Northwest. Forest Ecology and Management. 2019;450.
37. Whitlock C, Colombaroli D, Conedera M, Tinner W. Land-use history as a guide for forest conservation and management. Conservation Biology. 2018;32(1):84-97.
38. Willis KJ, Birks HJB. What is natural? The need for a long-term perspective in biodiversity conservation. Science. 2006;314(5803):1261-5.
39. Gillson L, Marchant R. From myopia to clarity: sharpening the focus of ecosystem management through the lens of palaeoecology. Trends in Ecology & Evolution. 2014;29(6):317-25.
40. Adolf C, Wunderle S, Colombaroli D, Weber H, Gobet E, Heiri O, et al. The sedimentary and remote-sensing reflection of biomass burning in Europe. Global Ecology and Biogeography. 2018;27(2):199-212.
41. van Leeuwen JFN, Froyd CA, van der Knaap WO, Coffey EE, Tye A, Willis KJ. Fossil Pollen as a Guide to Conservation in the Galapagos. Science. 2008;322(5905):1206-.
42. Larson ER, Johnson LB, Wilding TC, Hildebrandt KM, Kipfmueller KF, Johnson LR. Faces in the Wilderness: a New Network of Crossdated Culturally-Modified Red Pine in the Boundary Waters Canoe Area Wilderness of Northern Minnesota, USA. Human Ecology. 2019; 47(5):747-764.
43. Conedera M, Colombaroli D, Tinner W, Krebs P, Whitlock C. Insights about past forest dynamics as a tool for present and future forest management in Switzerland. Forest Ecology and Management. 2017;388:100-12.
44. Connor SE, Vanniere B, Colombaroli D, Anderson RS, Carrion JS, Ejarque A, et al. Humans take control of fire-driven diversity changes in Mediterranean Iberia's vegetation during the mid-late Holocene. Holocene. 2019;29(5):886-901.
45. Colombaroli D, Tinner W. Determining the long-term changes in biodiversity and provisioning services along a transect from Central Europe to the Mediterranean. Holocene. 2013;23(11):1625-34.
46. Gavin DG, Hallett DJ, Hu FS, Lertzman KP, Prichard SJ, Brown KJ, et al. Forest fire and climate change in western North America: insights from sediment charcoal records. Frontiers in Ecology and the Environment. 2007;5(9):499-506.
47. Bergeron Y, Cyr D, Girardin MP, Carcaillet C. Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. International Journal of Wildland Fire. 2010;19(8):1127-1139.
48. Hennebelle A, Grondin P, Aleman JC, Ali AA, Bergeron Y, Borcard D, et al. Using paleoecology to improve reference conditions for ecosystem-based management in western spruce-moss subdomain of Quebec. Forest Ecology and Management. 2018;430:157-65.
49. Cyr D, Gauthier S, Bergeron Y, Carcaillet C. Forest management is driving the eastern North American boreal forest outside its natural range of variability. Frontiers in Ecology and the Environment. 2009;7(10):519-24.
50. Verschuren D, Laird KR, Cumming BF. Rainfall and drought in equatorial east Africa during the past 1,100 years. Nature. 2000;403(6768):410-4.
51. Boer MM, Price OF, Bradstock RA. Wildfires: Weigh policy effectiveness. Science. 2015;350(6263):920-.
52. North MP, Stephens SL, Collins BM, Agee JK, Aplet G, Franklin JF, et al. Reform forest fire management. Science. 2015;349(6254):1280-1.
53. Petrokofsky G, Holmgren P, Brown ND. Reliable forest carbon monitoring - systematic reviews as a tool for validating the knowledge base. International Forestry Review. 2011;13(1):56-66.
54. Whitlock C. Land management - Forests, fires and climate. Nature. 2004;432(7013):28-9.

PAGES PAST GLOBAL CHANGES
GLOBAL PALEOFIRE WORKING GROUP 2
ROYAL HOLLOWAY UNIVERSITY OF LONDON
QRA Quaternary Research Association
cnrs CHRONO ENVIRONNEMENT