Title

Interdisciplinary solutions and collaborations for wildfire management.

Journal

iScience, 27(8)

Authors

Johnston, Fay

Jones, Charles

Li, Fang

et al.

Publication Date

2024-08-16

DOI

10.1016/j.isci.2024.110438

Backstory

Interdisciplinary solutions and collaborations for wildfire management

Fay Johnston,[1] Charles Jones,[2] Fang Li,[3] Alejandra Stehr,[4] Miguel Ángel Torres-Vázquez,[5] Marco Turco,[5] and Sander Veraverbeke[6,7]

The Earth system has long lived with fires,[1,2] but the impact of climate change on fire regimes has led to extreme wildfire events with higher intensity and faster spread.[3–5] This has effects on ecosystems and resources, air pollution, and, ultimately, human societies.[6] Facing these compounding challenges require interdisciplinary solutions and collaborations. In this Backstory, we bring together fire researchers across fields, aiming to foster discussions and collaborations across disciplines, for us to better understand how we can learn to "live with fire".

Beginnings

What are the greatest challenges facing wildfire research?

Charles Jones, University of California Santa Barbara: Wildfires result from complex interactions among weather, vegetation, and topographic features. Extreme fire-weather conditions arise from high winds, high temperatures, high vegetation fuel loadings, and low humidity. Global warming has modified the Earth's climate in ways that profoundly affect the behavior of wildfires,[3] but mechanisms are not well understood. Variable seasonal precipitation interspaced with severe droughts has changed vegetation and ecosystems. Warmer temperatures, heat waves, and high wind speeds combine with vegetation changes to create extreme fire-weather behavior.[7] The complexity of wildfires is further exacerbated by the human dimension. In addition to natural ignitions caused by lightning, human activity plays a significant role in

Above image: Helicopter flying through smoke caused by brush fire behind houses. (Photo from Getty images).

Wildfire near houses in Southern California. (Photo from Getty images).

wildfire ignitions.[8] These can happen from accidents (e.g., car exhaust pipes in rural roads), arson, powerline failures, hiking trail cleaning, and many others. Once ignited under extreme fire weather conditions, wildfires can grow substantially fast into large fires creating high-risk conditions for human life and property losses.[9]

Fang Li, Institute of Atmospheric Physics, Chinese Academy of Science: Accurately quantifying and predicting the interactions between wildfires and various factors, such as climate change, ecosystems, and human activities, remains one of the largest challenges in wildfire research. As wildfires become more frequent and severe due to climate change and land use,[3,5] the need for advanced research in this area grows more critical. Currently, most research focuses on wildfires' spatial and temporal variability characteristics and their driving factors. Yet, a comprehensive quantitative insight into wildfires' impacts across time, space, and spheres is still in the early stages.

Sander Veraverbeke, Vrije University Amsterdam: Wildfire science is intrinsically a highly interdisciplinary field. This makes it a very interesting field but also introduces complexities. Vegetation, climate, and human activity: these factors are all important for how wildfires behave and how fire regimes might change in the future. To me, these are some of the grand challenges of wildfire research: what is the relative importance of these different driving environmental factors on wildfires? How are they different in different regions on Earth? How do interplay? And how might they change in the future?

Marco Turco and Miguel Ángel Torres-Vázquez, University of Murcia: Fire is a fundamental component of the Earth's system, essential for maintaining ecosystem services that have supported human societies for millennia.[2] In regions with dense urban-wildland interfaces, wildfires can have devastating consequences, exacerbated by climate change, which is likely to increase the frequency of fire-conducive weather conditions.[4] Understanding changes in fire regimes and their drivers are crucial for developing effective fire management and prevention strategies. Despite advancements in datasets and research, significant gaps remain, particularly in linking climate and fire dynamics, understanding fire risk evolution, and projecting long-term climate impacts on fires globally.[3] Addressing these gaps are vital for adapting fire management systems to future climatic conditions.

Fay Johnston, University of Tasmania: Rapidly changing fire regimes, including more frequent and extreme fire behavior,[3,5] are challenging the limits of hard-won knowledge from research and previous generations of land managers and custodians. One example is managing prolonged and widespread degraded air quality. It is well established that smoke from landscape fires has extensive geographic reach affecting

[1]Menzies Institute for Medical Research, University of Tasmania, Hobart, Tasmania, Australia
[2]Department of Geography, University of California Santa Barbara, Santa Barbara, CA, USA
[3]International Centre for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[4]Faculty of Engineering, University of Concepción, Concepción, Chile
[5]Regional Atmospheric Modelling (MAR) Group, Department of Physics, Regional Campus of International Excellence Campus Mare Nostrum (CEIR), University of Murcia, 30100 Murcia, Spain
[6]Faculty of Science, Earth and Climate, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
[7]School of Environmental Sciences, University of East Anglia, Norwhich, United Kingdom
https://doi.org/10.1016/j.isci.2024.110438

population centers large distances from wildfires. Wildfire smoke pollution is responsible for a substantial annual burden of illness and death each year, far exceeding the direct toll of destructive fire fronts. The increased frequency and severity of wildfire activity have become major sources of air pollution,[6] especially in temperate and boreal regions, and now risk undoing air quality improvements in urban airsheds made over decades through addressing sources such as vehicle and industrial emissions. This not only affects human health by driving up population rates of heart, lung, and brain diseases, but also because of greenhouse gases and aerosols contributes to a vicious cycle driving a hotter, drier, and more fire prone planet.

Rapidly changing fire regimes are challenging the limits of hard-won knowledge from research and previous generations of land managers and custodians.

Alejandra Stehr, University of Concepción: Research related to fires is very broad, ranging from the necessary territorial and climatic conditions for fire initiation, to how fire spreads in the territory and the consequences once the fire is over. The literature related to post-fire consequences on hydric resources, for example, is fragmented. There are studies that focus on hydrological impacts such as post-fire flow, increases in flooding, or decrease in infiltration; and studies focusing on the consequence of the discharge of sediments and ash into water bodies, which in turn can produce turbidity, changes in the nutrients and metals.[10] In Chile, although there is some research related to the post-fire effect on water quantity in areas with plantations and other land uses, this has been carried out in micro-watersheds, where the physical processes that govern the hydrological cycle are different from mesoscale watersheds. There are also no studies that analyze the effect of fires on water quality and how long it takes for water to recover to pre-fire levels. At a global level, these studies are scarce, differ in results, and do not focus on long timescales. The main challenge related to the study of water resources after a fire is to generate a set of data on the effects of fires on soils, and how they in turn affect both water availability and water quality. In addition to understanding the timescale on which these effects occur, it is necessary to develop public policies to address these issues.

Interdisciplinary solutions and collaborations

How can interdisciplinary research and collaborations address these challenges?

M. Turco and M.Á. Torres-Vázquez: Fires are a complex issue. The synergistic effect between fires and underlying factors like fuel load and weather conditions can explain unusually large fire events.[1,9] Interdisciplinary research is essential for understanding how fires respond to climate change, requiring the integration of modeling advances with the practical application of climate information to assess impacts and provide actionable information.[11] This collaborative approach is crucial for developing effective fire management strategies that mitigate the effects of adverse climate conditions. By combining expertise across fields such as climatology, remote sensing, natural hazards, ecosystem dynamics, and modeling, interdisciplinary teams can push the boundaries of current knowledge and applications. Interdisciplinary research enhances our ability to translate cutting-edge scientific advances into societal benefits,[12] addressing challenges highlighted by national, European, and international research programs, such as the UN Sustainable Development Goals.

S. Veraverbeke: Given the interdisciplinary nature of wildfire science, one must collaborate to advance the field. Ecologists, climate and atmospheric, and behavioral scientists need to cross bridges to overcome these challenges. For example, global fire models capture some of these relationships between the environment, people, and fires, but they still do this in a relatively crude way. We now have unprecedented access to many large climate and satellite datasets. These datasets can be leveraged to reveal and better understand relationships about how people and the environment interact with fires.

F. Li: Wildfires are a critical component of the Earth system, influenced by and influencing weather, climate, ecosystems, and human activities.[1,2] They change vegetation composition and functioning, carbon and energy cycles, water availability and quality, sea ice, permafrost, and regional and planetary-scale atmospheric circulation, necessitating interdisciplinary collaboration across atmospheric science, ecology, physics, and cryosphere science. Furthermore, the effects of wildfire smoke on air quality and human health demand joint efforts from public health experts and environmental scientists to develop effective health advisories and community responses.[6] Addressing the socio-economic impacts, including property destruction, livelihood losses, and strains on healthcare and insurance systems, further requires the expertise of economists and sociologists. In addition, quantitative assessments of wildfires' impacts require collaborations among specialists in modeling, remote sensing, and field experiments to calibrate models with observations, and integrating local studies into regional and global wildfire research presents an additional challenge. Experts from diverse backgrounds are needed to delve into their specific areas of expertise while also understanding how these areas interact within the broader context of wildfire impacts. Only through such a comprehensive and integrated effort can we advance our quantitative understanding of wildfires' roles in the Earth system.

A. Stehr: The effects of wildfires are multidimensional and cannot be analyzed in a disciplinary way. For example, to understand why water quality is changing, one must investigate the changes in the composition of the soil, the ash that is left on the soil, which is washed into the

watercourses with precipitation. These physical changes influence the chemistry of the soil, and thus the components that are washed into water bodies. Hydrologists must work together with soil scientists, chemists, and biologists who study the recovery of the flora and fauna of the area. This will allow a better interpretation of the results, and understanding of the processes involved, allowing for better management measures to be taken. The FIRING project "Multi-scale effects of extreme forest fires on erosion, water, and biogeochemical cycles in natural and managed forest soils" (https://proyectofiring.cl/), financed by the Chilean National Agency for Research and Development, is an example of how researchers are trying to address the need for interdisciplinary collaborations.

The most difficult part of working together across disciplines is to ensure that the research is conducted in an interdisciplinary rather than a multidisciplinary way. What often happens is that each of us sets up our experiment and then the results are put together, which does not allow us to advance adequately in the construction of knowledge.

How can researchers and policymakers work together to improve wildfire resilience?

F. Li: Fostering a proactive partnership between researchers and policymakers is crucial to enhancing wildfire resilience. Researchers can provide valuable, data-driven insights that shape effective policies. They can predict fire risks and evaluate how different fire management policies affect fire regimes and the implications for local and broader-scale climate, ecosystems, and human health. This approach uses numerical experiments, which are cost-effective and efficient compared to real-life fire scenarios. Policymakers, on the other hand, play an essential role in translating these scientific insights into actionable strategies and integrating them into community planning and regulations. Regular workshops and joint task forces ensure that scientific advice directly informs policymaking. Such collaboration ensures that policies are scientifically grounded and strategically executed to maximize wildfire resilience.

Fostering a proactive partnership between researchers and policymakers is crucial to enhancing wildfire resilience.

A. Stehr: One of the biggest challenges we face as a society is how research results are transferred to the community and to public policy making. How do we, as scientists, manage to express the results obtained in such a way that they become a real input for new policies or laws. To do this, we must first build trust. The creation of committees of experts who work together with decision-makers is a good strategy to make this work. In the Chilean case, large areas are covered only by pine or eucalyptus trees, so the question when wildfires happen is: does a different composition of the landscape reduce the risk? Does it change the speed of recovery after a fire, among many others? How can we, within territorial planning, achieve a landscape that reduces the risk to communities?. The answers to these questions require years of work, which does not match political timescales. Having expert committees that go beyond governments is an opportunity to move forward in a better way to improve resilience to wildfires.

M. Turco and M.Á. Torres-Vázquez: To improve wildfire resilience, researchers and policymakers must collaborate closely, integrating scientific advancements into practical strategies. The increase in exposure to large wildfires[13] requires expanding fire management beyond suppression to include prevention and adaptation measures. Early prediction systems and seasonal forecasts can optimize resource allocation and preparedness, particularly in vulnerable wildland-urban interfaces. Tailored climate services and sustainable fuel management practices, combined with continuous dialogue and co-production of climate information, will enhance ecosystem resilience and ensure actionable, effective fire management strategies.[14,15]

S. Veraverbeke: The most important point here is that wildfire regimes are always regionally specific, based on the natural and sociocultural landscape characteristics. So, while we can find some general trends in how fires are changing on Earth and these can lead to some general evidence-based policy guidelines, these guidelines will always need to be translated to regional mitigation and adaptation measures. In this process, regional land and fire managers should play a critical role.

Fire can disproportionately affect some areas and communities. How can everyone (researchers and non-researchers alike) better serve these communities?

S. Veraverbeke: Fire is and will remain part of our lives, so we need to find harmonious ways to live with fire. Most fatal and extreme fire impacts on peoples' lives and infrastructure occur in the wildland-urban interface, where vegetation and "urban" fuels are intermixed. Taking away this mixture is a key to reducing fatalities and economic losses. This could be done at local scales, for example by removing fuels in backyards, to regional scales, for example by creating buffer zones near the wildland-urban interface through vegetation management. Note that these local and regional measures can reduce wildfire impacts on communities; however, the increases in wildfire extremes are a global problem driven by climate change. The only way to globally further halt such fire extremes is to stop or reduce emitting greenhouse gases.

Fire is and will remain part of our lives, so we need to find harmonious ways to live with fire.

F. Li: Effective collaboration across all stakeholders, with a clear focus on local needs and conditions, is essential for mitigating fire risks and enhancing community resilience. First, researchers could utilize remote sensing and advanced modeling to pinpoint communities at high risk for wildfires. By collaborating with community leaders, they can develop tailored fire management strategies that may involve adjusting land-use policies and enhancing local ecosystem resilience. Second, community leaders play a crucial role in implementing these strategies and ensuring they fit the specific needs and contexts of their communities. Third, public education and training are vital. Targeted programs could be established to enhance fire prevention awareness and self-protection capabilities among residents. In addition, local businesses and volunteers are encouraged to engage in direct fire prevention efforts, such as creating firebreaks and maintaining alert systems. Their participation can also extend to providing emergency aid and support after a fire.

M. Turco and M.Á. Torres-Vázquez: Both researchers and non-researchers can adopt several key strategies.[16] First, integrating fire science with local knowledge, especially from indigenous communities, can enhance fire management practices by combining traditional wisdom with modern techniques. Additionally, resources should be allocated before, during, and after wildfires to support at-risk communities, ensuring equitable access to necessary services and recovery efforts. Education and outreach programs can empower these communities with knowledge about fire risks and preparedness, fostering resilience, and self-sufficiency. Furthermore, mitigating emissions is crucial to reducing the broader impacts of climate change, which exacerbate wildfire risks. Collaborative efforts that include diverse stakeholders can lead to more inclusive and effective fire management strategies, ultimately promoting greater equity and sustainability in fire-prone regions.

A. Stehr: The best way for researchers to help these communities is by: (a) identifying the areas most at risk from wildfire, where one of the important considerations is how we assess exposure and vulnerability. It is in the latter that what is indicated in question 2 is fundamental, as we need to work in an interdisciplinary way including the social sciences; (b) delivering results to local authorities that are easily understandable and which can be translated into key measures and actions; (c) work together with local authorities to educate the community, making them aware of the risks they are exposed, showing them the actions that they can take to reduce the risk, and thus making them part of the solution.

Scientists should work together with local authorities to educate the community and make them aware of the risks they are exposed to, show them the actions that they can take to reduce the risk, and thus make them part of the solution.

F. Johnston: There are lots of inequities in the burden of wildfire smoke pollution that largely relate to interacting social and medical factors. Older and younger people, those who are more disadvantaged or who live with any kind of long-term medical condition, and those who work outside, including remote area firefighters, are disproportionately affected. People in these groups can be geographically dispersed and are often far from the fire fronts that generate the air pollution but can also include First Nations communities that live in close proximity to wildfire affected areas. For this reason, the human burden associated with smoke impacts is less visible, and rarely at the forefront of discussions about wildfire and this has hindered progress in advancing knowledge and practice to protect those who are most vulnerable. Key ways to better serve these more vulnerable groups include basic public health approaches—affordable and accessible healthcare, including prevention, education, and timely information, and access to evidence-informed interventions to reduce exposure such as well-fitted, particle filtering face masks, low-cost portable air filtration units, and access to cleaner, and in hot weather, cooler public air spaces. While there is still a lot to learn, the key gap is in implementation. We are far less good at implementing the preventive and responsive approaches that we know will work, than we are at enumerating the problems.

C. Jones: Research-specific disciplines can make substantial advances to further understand mechanisms involved in fire behavior, but inter-disciplinary collaborations can address wildfire issues from a holistic approach and develop efficient adaptation and mitigation strategies.[12] Santa Barbara in California is an area prone to wildfires and serves as a good example where universities, local, state, and federal agencies, and local communities work together to increase resiliency to wildfires. For example, the University of California in Santa Barbara works closely with the National Weather Service to better understand and forecast extreme fire weather conditions. This knowledge is transferred to local fire agencies, which in turn work with local communities such as the Fire Council and residents in the wildland urban interface. Vegetation management such as defensible spaces around homes and prescribed fires decreases the likelihood of large fast spreading fires. When fires occur, they can quickly be kept under control. Furthermore, frequent workshops and outreach events create a sense of community and increase awareness of solutions to mitigate the risks of wildfires.

Interdisciplinary collaborations can address wildfire issues from a holistic approach and develop efficient adaptation and mitigation strategies.

Opportunities

Going forward, what needs to happen for us to "learn to live with fire"?

F. Johnston: Interdisciplinary research, including practitioners, policy makers, and affected community groups is crucial. The expertise required spans many fields from meteorology, fire ecology, land management, disaster response, clinical medicine, and epidemiology, to public health. Advances made in one area can have massive repercussions in others, the classic example being long-standing policies of fire suppression in North America that are now contributing to the increased risk of extreme fires due to fuel accumulation. Disregarding the health burden of smoke in implementing fuel management strategies is another. Burning may be less costly to implement per area treated than non-burning methods such as mechanical thinning or controlled herbivory, but can be far more costly in public health impacts. Public health provides well-tested frameworks for evaluating large-scale interventions, including identifying and considering the risks, benefits, and complex trade-offs between these for a range of interventions compared with no action. A reactive "command and control" approach, is highly appropriate for disasters, but ill-suited to long-term planning, management, and support for social changes required to sustainably live with fire and smoke. More effective health economic analyses that quantify the costs of wildfire smoke are important for motivating more effected fire management policies. A public health spotlight on smoke also contributes to a better accounting of greenhouse pollution from uncontrolled wildfires. More intensive fuel management that involves First Nations and rural communities has co-benefits of reducing air pollution and providing economic and social opportunities for disadvantaged groups that often bear the brunt of wildfire disasters.

S. Veraverbeke: Living with fire is indeed the way forward. When doing so, it is also important to recognize the many ecological and sociocultural benefits that fire brings to nature and society. In times of climate change, it will be important to mitigate the negative impacts of extreme fires on society (for example, damage to infrastructure and air pollution). Awareness of the general public is critical for this, and education can play an important role in this. Most fires on Earth have a human origin, whether intentional or not, and many fires could thus be prevented. Given the ecological and other benefits, we would not want to prevent all fires, but these fires that burn should do that in an environment and climate that allows the least possible disruption to society.

F. Li: To adapt to a future with more frequent and more destructive wildfires, we should embrace an integrated approach.[6]

(1) Building fire-resilient communities: adopt fire-resilient building materials and designs, implement comprehensive land-use planning, and enhance community evacuation and emergency response strategies.

(2) Improving the accuracy of modeling wildfires and their influence for better preparation and response.

(3) Employing sustainable land and fire management strategies, such as prescribed burns, to reduce the occurrence of extreme fire disasters and to maintain the health of fire-dependent ecosystems. This approach reflects a profound lesson learned in US fire management: exclusive reliance on fire suppression leads to fuel accumulation, which in turn causes megafires.

(4) Enhancing air quality monitoring systems and issuing timely public health advisories to minimize the adverse public health impacts of wildfire smoke.

(5) Increasing public awareness about wildfire risks and mitigation strategies through education programs will help communities coexist more safely with fire.

A. Stehr: In the case of Chile, binding land management is needed to reduce exposure. And above all, risk communication to the community needs to be improved, so that they know clearly what they may face and can make informed decisions as to whether they want to continue living in areas at high risk of wildfire or not.

M. Turco and M.Á. Torres-Vázquez: To "learn to live with fire," we need a comprehensive approach that integrates scientific knowledge with practical strategies for fire management.[6] First, we must recognize fire as a natural and inevitable part of many ecosystems, moving beyond a "suppress all the fires" approach to one that embraces the ecological role of fire in sustaining biodiversity and ecosystem services. This involves adopting a framework that considers the complex interactions between human communities and their natural environments, focusing on reducing vulnerabilities and enhancing resilience. Improved land-use planning is crucial; governments and communities must collaborate to develop and enforce building codes and land-use policies that minimize fire risks, particularly in the wildland-urban interface. Early warning systems and better fire prediction models can help manage fire risks proactively, while sustainable fuel management practices, such as prescribed burns and mechanical treatments, can reduce fuel loads and fire intensity. Efforts to mitigate climate change are also essential. Reducing

We must recognize fire as a natural and inevitable part of many ecosystems. This involves adopting a framework that considers the complex interactions between human communities and their natural environments, focusing on reducing vulnerabilities and enhancing resilience.

emissions can help address one of the root causes of increased fire risk.[17] By integrating these strategies, we can develop a more resilient coexistence with fire, minimizing its adverse impacts while benefiting from its ecological roles.

Conclusions

C. Jones: While wildfires are part of Nature, climate change, and population growth into wildland-urban areas have made the situation much worse. The examples discussed previously illustrate solutions that can minimize the risks of wildfires.

ACKNOWLEDGMENTS

M.Á.T-V. and M.T. acknowledges the support of the ONFIRE project, grant PID2021-123193OB-I00, funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe". M.T. acknowledges funding by the Spanish Ministry of Science, Innovation and Universities through the Ramón y Cajal grant reference RYC2019-027115-I. The contribution of S.V. was funded by the European Research Council through a Consolidator grant under the European Union's Horizon 2020 research and innovation program (grant agreement No. 101000987) awarded to S.V. Dr. Camilla Imarisio aided in the construction of this Backstory, considering questions asked and overall curation of the piece.

REFERENCES

1. Bowman, D.M.J.S., Kolden, C.A., Abatzoglou, J.T., Johnston, F.H., van der Werf, G.R., and Flannigan, M. (2020). Vegetation fires in the Anthropocene. Nat. Rev. Earth Environ. *1*, 500–515. https://doi.org/10.1038/s43017-020-0085-3.
2. Pausas, J.G., and Keeley, J.E. (2009). A burning story: the role of fire in the history of life. Bioscience *59*, 593–601. https://doi.org/10.1525/bio.2009.59.7.10.
3. Jones, M.W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., Smith, A.J.P., Burton, C., Betts, R.A., van der Werf, G.R., et al. (2022). Global and regional trends and drivers of fire under climate change. Rev. Geophys. *60*, 3. https://doi.org/10.1029/2020RG000726.
4. IPCC (2021). Climate Change 2021: The Physical Science Basis. In Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, and C. Péan, eds. https://www.ipcc.ch/report/ar6/wg1/.
5. Cunningham, C.X., Williamson, G.J., and Bowman, D.M.J.S. (2024). Increasing frequency and intensity of the most extreme wildfires on Earth. Nat. Ecol. Evol. https://doi.org/10.1038/s41559-024-02452-2.
6. Moritz, M., Batllori, E., Bradstock, R., Gill, A.M., Handmer, J., Hessburg, P.F., Leonard, J., McCaffrey, S., Odion, D.C., Schoennagel, T., and Syphard, A.D. (2014). Learning to coexist with wildfire. Nature *515*, 58–66. https://doi.org/10.1038/nature13946.
7. Varga, K., Jones, C., Trugman, A., Carvalho, L.M.V., McLoughlin, N., Seto, D., Thompson, C., and Daum, K. (2022). Megafires in a Warming World: What Wildfire Risk Factors Led to California's Largest Recorded Wildfire. Fire *5*, 16. https://doi.org/10.3390/fire5010016.
8. Seto, D., Jones, C., Trugman, A.T., Varga, K., Plantinga, A.J., Carvalho, L.M.V., Thompson, C., Gellman, J., and Daum, K. (2022). Simulating Potential Impacts of Fuel Treatments on Fire Behavior and Evacuation Time of the 2018 Camp Fire in Northern California. Fire *5*, 37. https://doi.org/10.3390/fire5020037.
9. Pausas, J.G., and Keeley, J.E. (2021). Wildfires and global change. Front. Ecol. Environ. *19*, 387–395. https://doi.org/10.1002/fee.2359.
10. Pacheco, F.A.L., and Sanches Fernandes, L.F. (2021). Hydrology and stream water quality of fire-prone watersheds. Current Opinion in Environmental Science & Health *21*, 100243. https://doi.org/10.1016/j.coesh.2021.100243.
11. Copes-Gerbitz, K., Sutherland, I.J., Dickson-Hoyle, S., Baron, J.N., Gonzalez-Moctezuma, P., Crowley, M.A., Kitchens, K.A., Devisscher, T., and Burr, J. (2024). Guiding principles for transdisciplinary and transformative fire research. fire ecol. *20*, 12. https://doi.org/10.1186/s42408-023-00244-w.
12. Shuman, J.K., Balch, J.K., Barnes, R.T., Higuera, P.E., Roos, C.I., Schwilk, D.W., Stavros, E.N., Banerjee, T., Bela, M.M., Bendix, J., et al. (2022). Reimagine fire science for the anthropocene. PNAS nexus *1*, pgac115. https://doi.org/10.1093/pnasnexus/pgac115.
13. Bowman, D.M., Williamson, G.J., Abatzoglou, J.T., Kolden, C.A., Cochrane, M.A., and Smith, A.M. (2017). Human exposure and sensitivity to globally extreme wildfire events. Nat. Ecol. Evol. *1*, 0058. https://doi.org/10.1038/s41559-016-0058.
14. Turco, M., Jerez, S., Doblas-Reyes, F.J., AghaKouchak, A., Llasat, M.C., and Provenzale, A. (2018). Skilful forecasting of global fire activity using seasonal climate predictions. Nat. Commun. *9*, 2718. https://doi.org/10.1038/s41467-018-05250-0.
15. Turco, M., Marcos-Matamoros, R., Castro, X., Canyameras, E., and Llasat, M.C. (2019). Seasonal prediction of climate-driven fire risk for decision-making and operational applications in a Mediterranean region. Sci. Total Environ. *676*, 577–583. https://doi.org/10.1016/j.scitotenv.2019.04.296.
16. Kelly, L.T., Fletcher, M.S., Menor, I.O., Pellegrini, A.F., Plumanns-Pouton, E.S., Pons, P., Williamson, G.J., and Bowman, D.M. (2023). Understanding Fire Regimes for a Better Anthropocene. Annu. Rev. Environ. Resour. *48*, 207–235. https://doi.org/10.1146/annurev-environ-120220-055357.
17. Turco, M., Abatzoglou, J.T., Herrera, S., Zhuang, Y., Jerez, S., Lucas, D.D., AghaKouchak, A., Cvijanovic, I., and Cvijanovic, I. (2023). Anthropogenic climate change impacts exacerbate summer forest fires in California. Proc. Natl. Acad. Sci. USA *120*, e2213815120. https://doi.org/10.1073/pnas.2213815120.