Commentary

Technological solutions for living with fire in the age of megafires

Marta Yebra,[1,2,3,*] Robert Mahony,[2,3] and Robert Debus[3]
[1]Fenner School of Environment and Society, The Australian National University, Canberra, ACT, Australia
[2]School of Engineering, The Australian National University, Canberra, ACT, Australia
[3]Bushfire Research Centre of Excellence, The Australian National University, Canberra, ACT, Australia
*Correspondence: marta.yebra@anu.edu.au
https://doi.org/10.1016/j.oneear.2024.05.017

Anthropogenic climate change is driving extreme fire seasons, challenging the effectiveness of fire management practices developed over the last 50 years. New and diverse strategies are needed to achieve safe coexistence in an age of megafires. A redefinition of the wildfire management paradigm is central to the shift, placing greater emphasis on the adoption of high-tech solutions for early fire detection and rapid ignition suppression.

Fire is a natural process, an intrinsic element in many landscapes. It has shaped ecosystems, and it has been embedded in local, Indigenous cultural practices for thousands of years. However, anthropogenic activities such as industrialization, land clearance, human population growth and consequent climate change, the displacement of Indigenous fire cultural practices, and the subsequent adoption of large-scale firefighting and fuel management have significantly intensified fire activity.[1] A fire ignited 200 years ago in the Australian bush would have had a vastly different outcome to the "Black Summer" fires of 2019 and 2020. That disaster stood out for its unprecedented scale, encompassing 23 million hectares of forest, significant radiative power, and hundreds of fires evolving into extreme pyroconvective events. Nearly 20% of Australia's eucalypt forest was affected, the largest extent since at least 1851.[2]

Over the last 50 years, two main strategies, suppression and prescribed burning, have been adopted globally to manage fire-prone landscapes to reduce the risk of catastrophic wildfires and to promote safer coexistence with fire. Suppression involves actively fighting wildfires to prevent them from spreading and causing damage. Prescribed burning, also known as controlled burning, involves the deliberate and planned setting of fires by trained professionals under specific conditions to achieve a reduction of accumulated fuel and to reduce potential fire impacts.

These practices differ from traditional Indigenous fire management, which tends to be smaller in scale and more localized, aligning with cultural objectives. Contemporary land management strategies are beginning to integrate traditional Indigenous practices with modern approaches. However, suppression continues to be the primary method of wildfire management.[3]

Neither of these two fire management strategies are without drawbacks. Recent research indicates that prescribed burning can disturb natural forests and exacerbate long-term flammability potential.[4] However, any reduction in prescribed burning can only increase dependence on fire suppression strategies, which in turn have become increasingly costly[5] and inefficient under extreme fire risk conditions. At the same time, other recent studies suggest that aggressive fire suppression efforts may paradoxically intensify wildfire severity and amplify the impacts of climate change and fuel accumulation in the longer term.[6]

In these difficult circumstances it appears that a staged approach to fire suppression is appropriate. Suppression activity must necessarily be intense and rapid in the case of ignitions that risk growing into high-intensity catastrophic fires. These actions should be more moderate in the case of ignitions that will lead to the lower-intensity fires that are more consistent with the natural cycle of flammable landscapes like the Australian bush.

Navigating complexity in fire management decision-making

Any decision about the timing of prescribed burning, or any decision about whether to suppress a fire or not, requires the consideration of a variety of factors, such as weather conditions, terrain, landscape flammability, fuel availability, available firefighting resources, and potential impacts on ecosystems and communities. An appropriate balance of these elements is crucial to effective and strategic management decision-making in fire-prone areas. However, this balance is becoming more and more difficult to achieve. This is because the frequency, size, and severity of wildfires are projected to continue increasing.[1] Flammability levels are especially critical to any decision about suppressing a fire or letting it run. By the end of the century, forests are expected to become highly flammable for an additional 30 days per year,[7] so vegetation will be even more likely to ignite and sustain flames. Flammability is influenced by a range of factors across various scales, such as leaf moisture, fuel distribution, vegetation density, seasonal changes, and fuel layer complexity.[8] As an example, reduced rainfall and prolonged droughts, observed globally from Canada to Australia, disrupt natural flammability controls and typically turn moist valleys into environments where even small fires can quickly escalate into large scale megafires before intervention is feasible. The threat extends beyond traditional fire-prone areas. Regions like central Europe, Scandinavia, and the Amazon are anticipated to face heightened risks in the coming decades.[7]

Increasingly dry landscapes adds complexity to the task of balancing conventional and traditional practices. As suitable days for prescribed and cultural burning are reduced and the available response time for initial attack success diminishes, it becomes more difficult to sustain lower-intensity fires in the landscape.

Early detection and suppression are critical

Escaped fires pose significant threats to communities and entail substantial suppression costs.[9] The availability of accurate and timely fire location information allows fire crews to arrive at fires earlier, enhancing the prospect of initial attack success and supporting more detailed planning for larger fires.[9]

However, it is inevitable that unplanned wildfires often ignite unnoticed, complicating accurate later determination of their locality. This is especially significant in the context of lightning ignitions, which currently contribute 77% to the total area burned during wildfires in forested extratropical regions, including the western United States, southeast Australia, eastern Siberia, and western Canada.[10] Moreover, with each degree of warming, the frequency of lightning ignitions is projected to increase by 11%–31%.[10] Lightning strikes present a unique challenge because they frequently occur in remote and inaccessible areas, decreasing the likelihood of initial attack success.[9] Although meteorological services can predict weather events, a dry lightning storm typically involves thousands of lightning strikes, which can only be located with limited accuracy. It is time consuming and dangerous to inspect all potential ignition points.

Lightning strikes also occur predominantly in the afternoon and early evening, adding the complication of darkness to detection and early suppression. Safety concerns and logistical constraints often limit crews and aircraft to daylight operations. Trials of night-time operations, including the use of night vision devices in helicopters, are being undertaken in countries like Australia and the US, but it remains difficult to address newly ignited fires promptly outside daylight hours. Moreover, it is essential to recognize the observed changes in night-time fire behavior. Nights are becoming warmer and drier, creating more favorable conditions for fire spread and depriving firefighters of night-time relief. Globally, night-time fires became 7.2% more intense between 2003 and 2020.[11]

The new challenges relating to fire detection and firefighting, especially during night-time hours, require innovative strategies and technologies to protect lives, property, and natural resources.

Technologies for early fire detection and suppression

Remote sensing technology can predict which landscapes will be most vulnerable to fire. Satellites play a role in assessing ecosystem flammability by monitoring vegetation and identifying areas susceptible to ignition and rapid fire spread and therefore, permitting more strategic planning and effective deployment of fire detection resources.[12] However, current satellite systems do not adequately address the unique difficulty of identifying all the vegetation traits that make the landscapes highly flammable. The development of specialized satellite technology tailored to monitor vegetation flammability at a landscape scale, such as the innovative OzFuel short-wave infrared (SWIR) multispectral instrument, represents a promising approach.[13] Aditionally, ongoing research into novel algorithms aims to improve early fire detection using existing satellite imagery.[14] Current satellite technologies, however, encounter difficulty in the detection of fires in their early stages due to limitations in the spatial or temporal resolution of sensors on both geostationary and low Earth orbit (LEO) satellites. Cloud cover can also hinder accurate detection by optical sensors on both types of satellite: a particular issue for lighting ignitions occurring during thunderstorms. SWIR sensors, with their ability to penetrate certain types of clouds, offer improved performance in such conditions, especially at night-time.[15] Additional investment is needed to accelerate the advancement and validation of satellite technology and to fully demonstrate its ability to enhance decision-making.

However flammable a landscape may be, a fire will not occur without an ignition source. Lightning detection networks can identify potential sources of ignition by accurately locating strikes and by identifying specific attributes of lightning that contribute to ignition probability. Some lightning strikes display a particular characteristic, a long continuing current, thought to be responsible for most lightning ignitions,[16] but further research is needed to characterize lightning ignitions and to increase the accuracy of lighting strike detection.

Not all fires are caused by lightning. High tension power lines are also a source of ignition in remote bushland. Closer to population centers there are burnt cars, ignitions caused by trains, sparks from equipment such as angle grinders or chainsaws, firearms, glass refraction, electric fences, and more. Machine vision or thermal cameras installed on fire towers and other infrastructure such as transmission towers can provide surveillance for heat or smoke indicating a growing ignition. Novel computer vision algorithms are being developed to segment smoke from images and estimate the location of fires, addressing some of the issues of false alerts in existing systems while enabling better discrimination of ignition points.[17] Ground based Internet of Things (IoT) sensors are also a powerful technology for fire detection. Such sensors measure temperature, humidity, air particles, and combustion gases and provide detailed information about fires even during the night. However, comprehensive ground level coverage of these sensors is expensive and therefore spatially limited.

The job is not finished once a fire is detected either. Characterizing the fire and providing emergency services with information that allows them to plan a suitable response is critically important. Drone fleets equipped with thermal sensors capable of validating ignitions identified by lightning detectors, ground based sensors, or cameras regardless of weather conditions or time of day offer a promising solution. Once an ignition is located and confirmed, a drone can circle the ignition site and provide fire services with real-time situational awareness of fire growth. Such information is critical in allowing effective prioritization of scarce resources to target responses to control and extinguish the most significant high-risk ignitions in remote bushland.

Finally, controlling and extinguishing a fire in remote bushland brings its own challenges. Remote-area fire teams (RAFTs) are specialized firefighting units that are deployed to remote or difficult to access areas by helicopter to control and extinguish wildfires. For safety

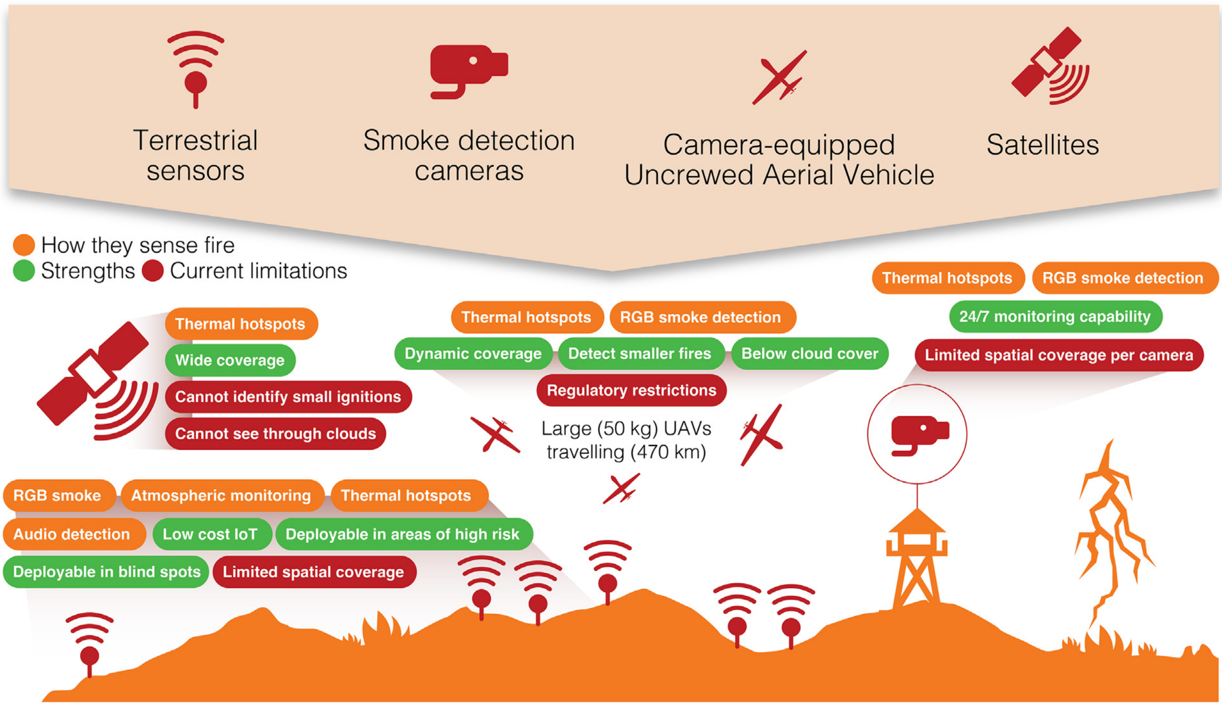

Figure 1. An overview of some fire-detection technologies
For each technology, the sensing methods, strengths, and limitations are highlighted.

reasons, RAFTs are limited to situations where they can get in and out safely even if there are changes in environmental conditions, such shifts in wind direction or other unforeseen challenges that might arise during their mission. Technology offers the potential to suppress fires at night and in adverse weather conditions. GPS-guided and cost-effective unmanned autonomous vehicles such as "water gliders" offer promising solutions.[18] These vehicles can be accurately deployed from high altitudes, even in inclement weather, enhancing the capacity to combat fires efficiently. Their adaptability for deployment by non-specialized aircraft further increases the available firefighting resources during crisis situations. Using autonomous drones to provide water drops and support for RAFTs is also an important technology that is under development.

Beyond the use of individual technologies, fire managers must be skilled in the selection of the optimal combination of fire-response solutions as each technology comes with its own strengths and limitations (Figure 1). We urge the research community to investigate integrated approaches to early fire detection and to thoroughly evaluate innovative technologies across a range of ignition type, weather, and fuel flammability scenarios. Understanding the strengths and limitations of different sensor modalities permits the design of solutions that address specific capability gaps and collectively enhance overall capacity. For example, a lightning detection network can be integrated with weather data and satellite-derived vegetation flammability information, such as that provided by OzFuel. Machine learning algorithms can then identify lightning strikes that are highly likely to start a fire. IoT sensors strategically located in high-risk areas, regions of high ecological value or spots not covered by other detection technologies, can promptly trigger alarms. In areas lacking IoT sensors near potential ignition points, fire tower cameras can autonomously focus on suspected ignition sites to monitor for signs of heat or smoke. Drones can then be deployed to verify these ignitions, prioritizing lightning strikes which have the potential to escalate into major fires or those occurring outside the coverage of the cameras. Drones can also provide situational awareness of fire propagation. Additionally, satellites can be tasked to gather data over ignition sites, further enhancing situational awareness. Detection by one or more of these technologies can trigger the rapid deployment of resources such as a water glider or manned water bomber to deliver fire retardant to contain small fires, thereby buying valuable time for RAFT crews to arrive to the scene.

Novel technologies such as the ones we have described offer the potential for more efficient detection and suppression of ignitions. Importantly, they can reduce resource demand while enhancing safety measures for firefighting personnel or ground crews, for instance, by minimizing their exposure to dangerous ground or airspace conditions. It is critical to integrate technologies and data sources and to understand the opportunities they bring for our understanding of wildfires and their prevention. Effective integration of these technologies will necessitate careful evaluation of their performance as a system, modeling to assess the cost-efficiency and a thorough assessment of the benefits of implementation compared to business-as-usual operations.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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.

2. Bowman, D., Williamson, G., Yebra, M., Lizundia-Loiola, J., Pettinari, M.L., Shah, S., Bradstock, R., and Chuvieco, E. (2020). Wildfires: Australia needs national monitoring agency. Nature *584*, 188–191.
3. Fernandes, P.M. (2013). Fire-smart management of forest landscapes in the Mediterranean basin under global change. Landsc. Urban Plann. *110*, 175–182.
4. Lindenmayer, D., and Zylstra, P. (2024). Identifying and managing disturbance-stimulated flammability in woody ecosystems. Biol. Rev. *99*, 699–714.
5. Thompson, M.P., Haas, J.R., Finney, M.A., Calkin, D.E., Hand, M.S., Browne, M.J., Halek, M., Short, K.C., and Grenfell, I.C. (2015). Development and application of a probabilistic method for wildfire suppression cost modeling. For. Pol. Econ. *50*, 249–258.
6. Kreider, M.R., Higuera, P.E., Parks, S.A., Rice, W.L., White, N., and Larson, A.J. (2024). Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. Nat. Commun. *15*, 2412.
7. Clarke, H., Nolan, R.H., De Dios, V.R., Bradstock, R., Griebel, A., Khanal, S., and Boer, M.M. (2022). Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. Nat. Commun. *13*, 7161.
8. Younes, N., Yebra, M., Boer, M.M., Griebel, A., and Nolan, R.H. (2024). A Review of Leaf-Level Flammability Traits in Eucalypt Trees. Fire *7*, 183.
9. Plucinski, M.P., Dunstall, S., McCarthy, N.F., Deutsch, S., Tartaglia, E., Huston, C., and Stephenson, A.G. (2023). Fighting wildfires: predicting initial attack success across Victoria, Australia. Int. J. Wildland Fire *32*, 1689–1703.
10. Janssen, T.A.J., Jones, M.W., Finney, D., van der Werf, G.R., van Wees, D., Xu, W., and Veraverbeke, S. (2023). Extratropical forests increasingly at risk due to lightning fires. Nat. Geosci. *16*, 1136–1144.
11. Balch, J.K., Abatzoglou, J.T., Joseph, M.B., Koontz, M.J., Mahood, A.L., McGlinchy, J., Cattau, M.E., and Williams, A.P. (2022). Warming weakens the night-time barrier to global fire. Nature *602*, 442–448.
12. Yebra, M., Quan, X., Riaño, D., Rozas Larraondo, P., van Dijk, A.I., and Cary, G.J. (2018). A fuel moisture content and flammability monitoring methodology for continental Australia based on optical remote sensing. Remote Sensing of Environment *212*, 260–272.
13. Younes, N., Yebra, M., Mathew, J., and Sharp, R. (2023). OzFuel: A Space-Based Vegetation Fuel Flammability Monitoring System (SPIE).
14. Kang, Y., and Im, J. (2024). Mitigating underestimation of fire emissions from the Advanced Himawari Imager: A machine learning and multi-satellite ensemble approach. Int. J. Appl. Earth Obs. Geoinf. *128*, 103784.
15. Wooster, M.J., Roberts, G.J., Giglio, L., Roy, D.P., Freeborn, P.H., Boschetti, L., Justice, C., Ichoku, C., Schroeder, W., Davies, D., et al. (2021). Satellite remote sensing of active fires: History and current status, applications and future requirements. Remote Sensing of Environment *267*, 112694.
16. Latham, D., and Williams, E. (2001). Chapter 11 - Lightning and Forest Fires. In Forest Fires, E.A. Johnson and K. Miyanishi, eds. (San Diego: Academic Press), pp. 375–418.
17. (2022). Transmission-guided bayesian generative model for smoke segmentation. In Proceedings of the AAAI Conference on Artificial Intelligence, S. Yan, J. Zhang, and N. Barnes, eds.
18. Yebra, M., Barnes, N., Bryant, C., Cary, G.J., Durrani, S., Lee, J.-U., Lindenmayer, D., Mahony, R., Prinsley, R., Ryan, P., Sharp, R., Stocks, M., et al. (2021). An integrated system to protect Australia from catastrophic bushfires. The Australian Journal of Emergency Management *36*, 20–22.