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BRIEF COMMUNICATION OPEN

Health costs of wildfire smoke to rise under climate change

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The global health burden from wildfire smoke is expected to worsen under climate change, yet we lack quantitative estimates of the economic costs of increased mortality and hospital admissions for cardiovascular and respiratory conditions. Using a quantitative wildfire risk assessment framework and a 12-member climate model ensemble, we find a median increase in wildfire smoke health costs of 1–16% by 2070 across diverse landscapes in south-eastern Australia. Ensemble maximum cost increases (5–38%) often exceed abatements from fuel treatment, while costs decline moderately (0–7%) for the ensemble minimum. Unmitigated climate change will increase the health burden of wildfire smoke and undermine prescribed burning effectiveness.

npj Climate and Atmospheric Science (2023)6:102 ; https://doi.org/10.1038/s41612-023-00432-0

Wildfire smoke exacts a serious toll on human health, with a range of short-term and long-term health risks depending on the size and components of particulate matter and the vulnerability of exposed populations[1]. Fine particles ($PM_{2.5}$) from wildfire smoke are disproportionately dangerous compared to other sources[2] and have been linked to increased mortality from cardiovascular and respiratory causes on a local and global scale[3]. Wildfire smoke can travel tens to hundreds of kilometres, potentially reaching major population centres[1].

Substantial economic costs are associated with health effects of wildfire smoke such as premature deaths, hospital admissions and emergency department presentations. Estimates from Australia, the United States of America and Canada range from $1.6 million to $6.1 million per 100,000 people for an average wildfire season[4–6], with these figures spiking dramatically during major wildfire events. The smoke-related health costs of the 2019–20 Black Summer forest fires in eastern Australia were $1.95 billion, almost four times higher than the next-highest season over the previous 20 years[7] (in this paper all figures are in Australian dollars, which are equivalent to 0.66 US dollars and 0.62 Euro as at 9 March 2023).

Fire regimes are changing globally[8] with burnt area and wildfire risk expected to increase in the absence of rapid and sustained cuts to greenhouse gas emissions[9,10]. One recent study suggested a potential tripling of particulate matter from wildfires under a high emissions scenario[11], suggesting a significantly increased future health burden. However, research on changing smoke exposure has focused largely on the U.S[12]. and quantitative assessments of the economic costs are lacking. One exception is Stowell et al.[13], who found that additional smoke-related asthma events could add US $1.5 billion (~2.1 billion AUD) per year to the health costs of wildfire smoke each season in the Western U.S. Here we provide a quantitative assessment of the impact of climate change on wildfire smoke-related health costs in a diverse range of fire-prone landscapes in south-eastern Australia (Fig. 1a). Our study employs a quantitative framework for fire risk assessment[14], testing climate change effects in the context of a range of realistic alternative management scenarios (fuel treatment options). In this framework, fire behaviour simulations are carried out in case study landscapes under a range of weather conditions and fuel treatments, with the results fed into risk analyses using Bayesian Decision Networks (see 'Methods'). This facilitates systematic evaluation of variation in the effectiveness of different strategies at mitigating a range of risks.

The future health costs of wildfire smoke varied widely depending on case study landscape, climate model ensemble member and fuel treatment option. Results for the Jervis Bay case study landscape in south-eastern NSW (south of Sydney) are broadly illustrative of responses of many of the case studies across the study area (Fig. 1b). The risk of wildfire—and hence smoke impacts on human health and associated economic costs—generally declined with increasing amounts of fuel treatment under present-day climate conditions, particularly where treatment was carried out close to people and properties (at the 'edge'). Landscape treatment had very modest effects on wildfire occurrence and hence wildfire smoke health costs. However, even at very high treatment rates the residual risk remained high i.e. smoke health costs were well over half (and often 80–90%) of the costs of a no-treatment scenario. These responses of wildfire smoke health costs to fuel treatment rate and location were projected to persist under climate change. The key difference was that for most climate model ensemble members, there was projected to be an increase in wildfire occurrence and hence smoke health costs (black bars in Fig. 1b). Only for the ensemble members with the most moderate projected changes (i.e. those with lower rises in temperature and increases rather than decreases in rainfall) did impacts remain relatively stable.

The greatest changes in wildfire smoke health costs were projected to occur in those landscapes where costs were already high, due to some combination of high fire likelihood and high population density (Fig. 2a). For a single average-sized fire (around 1000 hectares in today's climate), smoke health costs could increase by over $23,000 in the Blue Mountains (BM) landscape and by over $19,000 in Gloucester (GL). These increases corresponded to the climate model ensemble member with the greatest projected increase in fire weather conditions. At the other end of the spectrum, the ensemble member with the most moderate projected changes in fire weather was associated with a

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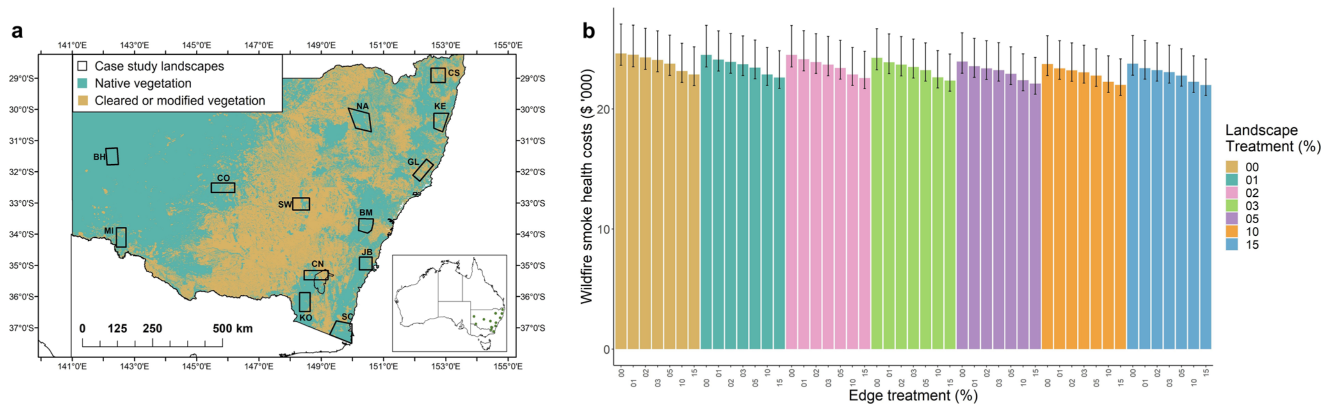

Fig. 1 Study area and climate change effects on wildfire smoke health costs in a single landscape. a 13 case study landscapes were drawn from a range of native (aqua) and modified vegetation (brown) in NSW, Australia. BH = Broken Hill, MI = Mildura, CO = Cobar, SW = Southwestern Slopes, NA = Nandewar, CN = Canberra, KO = Kosciuszko, CS = Casino, KE = Kempsey, GL = Gloucester, BM = Blue Mountains, JB = Jervis Bay, SC = Southeast Corner. **b** Wildfire smoke health costs associated with a single average-sized fire in the Jervis Bay (JB) landscape. Coloured bars represent different rates of landscape treatment (0–15% p.a.), individual bars within each set of coloured bars represent edge treatment rate (0–15% p.a.). Thick bars represent the reference period (1990–2009). Black 'error' bars show the range of a 12-member ensemble of projected climate change impacts by 2060–2079.

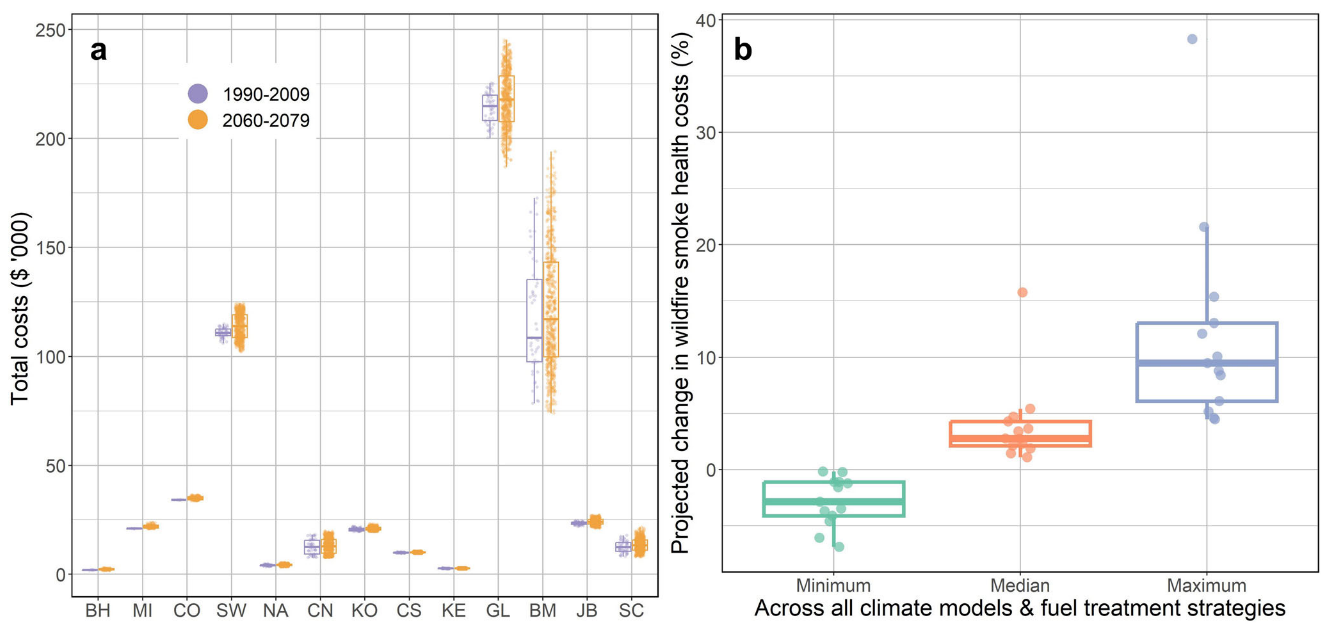

Fig. 2 Climate change effects on wildfire smoke health costs for all landscapes. a Purple markers show reference period (1990–2009) wildfire smoke health costs associated with a single average-sized fire in each landscape across all fuel treatment strategies ($n = 49$). Orange markers show future (2060–2079) wildfire smoke health costs for the same set of strategies, repeated for all 12 ensemble members ($n = 588$). See Fig. 1a for case study landscape details. **b** Range of projected changes in wildfire smoke health costs by 2060–2079 (relative to 1990–2009). Each marker represents an individual landscape. Out of the total 588 combinations of fuel treatment strategy ($n = 49$) and climate model ensemble member ($n = 12$), three values are shown: minimum, median and maximum. Each boxplot is based on a single data point for each landscape (centre line = median, box limits = upper and lower quartiles, whiskers = 1.5x interquartile range).

potential decline in the smoke health costs of over $15,000 in Gloucester and over $9000 in the Blue Mountains. In case study landscapes with smaller fires and lower population density—and hence lower current smoke health costs—the projected climate change impacts for a single fire were much lower (−$1000 to +$3800 for a single average-sized fire), even in landscapes which responded strongly to fuel treatment such as Canberra (CN) and Southeast Corner (SC). In relative terms, the median increase in the health costs of wildfire smoke due to climate change was 1–5% across 12 of the 13 landscapes investigated, considering all combinations of climate model ensemble and fuel treatment strategy (Fig. 2b). The median increase in the 13th landscape, Broken Hill (BH), was 16%, an outlier that may be partly due to its present-day costs being among the lowest of all landscapes. Focusing on the ensemble member with the most moderate climate changes, a decrease in costs of 0–7% was projected across the 13 landscapes. Conversely, for the ensemble member with the greatest amount of climate change, future smoke health costs increased by 5–22% in 12 landscapes, and by 38% in Broken Hill. For context, the ensemble member with the greatest changes in climate led to increases in wildfire smoke health costs that substantially offset, and in some cases eclipsed, the cost savings from even the highest rates of fuel treatment (Supplementary Table 2).

Climate change is expected to increase the economic costs associated with wildfire smoke impacts on human health in most cases, consistent with previous studies[11–13]. Baseline costs strongly influenced these results, with regions already exposed to high levels of wildfire smoke at greatest risk. Health costs of wildfire smoke were predicted to remain stable or decline moderately for climate models projecting less warming and increased rainfall. These results are robust across widely varying fuel treatment strategies, suggesting that higher rates of treatment may be required in the future to achieve the risk reduction levels of the reference period. For ensemble members projecting the greatest increase in fire weather conditions, the increased health costs from wildfire smoke exceeded the cost abatement of all fuel treatment strategies in some landscapes. Therefore no feasible treatment option will be likely to reduce overall health impacts and costs if the upper end of ensemble projections of climate change occurs. This suggests alternate risk mitigation strategies need to be considered, such as planning and construction standards, community education, fuel breaks and suppression.

These figures likely underestimate the true health costs of increased wildfire smoke under climate change because they apply to statistical distributions of an individual wildfire run over a single day. They do factor in the occurrence of very large fires (~200,000 ha) under extreme but rare weather conditions, but they do not account for fires burning over multiple days, multiple fires within a landscape, or impacts from neighbouring areas. These limitations could be addressed by expanded wildfire modelling frameworks[15]. Results are annualised and represent long-term risk in each landscape, meaning the smoke health costs of an individual extreme fire would be significantly higher than the figures reported here. Note also that our smoke-related cost model is also likely to underestimate impacts due to a focus on acute exposure and a single pollutant ($PM_{2.5}$)[4]. Our findings are constrained by the accuracy of our models for fire behaviour (including the fuel-fire-time relationship) and the smoke-cost relationship, and they do not include potential benefits or costs of fuel breaks or active fire suppression[16,17]. We used a quantitative risk assessment framework[14] which can incorporate such factors, as well as improved fire, smoke, health and cost models, as they become available.

Delaying strong climate action will increase risk of wildfire smoke impacts on human health under climate change. Importantly, our study does not include the health costs associated with prescribed fire smoke, which can be substantial and may even exceed wildfire smoke costs in years with moderate fire activity[4]. Accurately quantifying the trade-offs between wildfire and prescribed fire smoke remains challenging and more research is required to support the planning and operational decisions of fire and land managers in this complex area[18,19].

METHODS

Fire behaviour model

Thirteen fire-prone case study landscapes, each around 200,000 ha in size, were selected to capture some of the diversity within the south-eastern state of New South Wales, Australia, in terms of vegetation, climate, land use, settlement patterns and fire regimes (Fig. 1a). We simulated wildfire in these landscapes using PHOENIX RapidFire v4.0.0.7[20]. PHOENIX has multiple fuel classes and estimates fuel loads using a negative exponential growth function dependent on vegetation type[21]. Phoenix is currently the dominant fire behaviour simulator for operational and strategic use in south-eastern Australia. It has been extensively evaluated and found to perform reasonably overall, but with a tendency to underestimate extreme fire behaviour[22–24]. Key areas for model development include weather inputs, fuel models, spotting and fire severity. Fires were simulated with no fuel treatment and after carrying out varying rates of prescribed burning fuel treatment in either edge or landscape blocks. Edge blocks are adjacent to human settlements and infrastructure while landscape blocks are larger and more remote. We started fires in 1000 different locations with high ignition probability[25]. Individual fires were ignited at 1100 h and propagated for 12 h, unless self-extinguished within this period. This was repeated for up to 49 permutations of treatment (0, 1, 2, 3, 5, 10 and 15% of treatable vegetation within each case study landscape, for both edge and landscape block types). Treatment rates were achieved through random selection of burn blocks. The same ignition location was repeated for each treatment scenario. Weather data was drawn from local weather stations and repeated under the full range of locally occurring weather conditions, yielding ~100,000 simulated fires per landscape across the full set of fuel treatment strategies, ignition locations and weather conditions. The properties of the resultant fires were used to estimate the costs of wildfire smoke impacts on human health then adjusted for the frequency of fire weather conditions contributing to ignition likelihood and fire spread to estimate annualised risk (see Risk estimation below).

Risk model

We used a Bayesian Decision Network (BDN) to evaluate the risk mitigation available from fuel treatment[26]. Fire simulation output was used to estimate the probability distributions for area burnt by wildfire and wildfire smoke impacts on human health costs under the various weather and fuel treatment scenarios. These risks could be validly compared between regions because they reflect the observed distribution of fire weather conditions in each area. Model outputs represented a single average-sized fire in each landscape; at the landscape scale impacts would be several orders of magnitude greater. A zero edge, zero landscape treatment option ("do nothing") was used as a base case to explore the relative effects of treatment across landscapes and values, resulting in a measure of the residual risk after treatment. Climate change impacts on risk were calculated using a 12-member ensemble of dynamically downscaled fire weather projections, selected for skill, independence and the ability to span the broadest possible range in future climate[27,28]; Supplementary Table 3). They represent the projected climate under the A2 emissions scenario[29] for the period 2060–2079, compared to the reference period 1990–2009. This represents a relatively high emissions scenario, consistent with the global emissions trajectory at the time of the NARCliM ensemble design and suitable for exploring the consequences of unmitigated climate change. A2 represents 3.4 degrees of warming by the end of the 21st century (likely range 2.0 to 5.4 degrees[30]). This is broadly comparable to RCP8.5 with 3.7 degrees of warming (5 to 95% range 2.6 to 4.8 degrees[31]) and SSP3-7.0 with 3.6 degrees of warming (very likely range 2.8 to 4.6 degrees[32]). A new objectively designed and dynamically downscaled climate model ensemble is being developed for south-eastern Australia but was not available at the time of writing[33]. More information on the risk and fire behaviour models can be found in ref. [34].

Wildfire smoke health cost model

Smoke health costs were calculated from models presented in ref. [4]. They looked at air quality in the NSW monitoring network on days dominated by wildfires and used a quantitative health impact assessment framework to attribute the health costs of exposure to fine particulate matter for each type of fire. Their estimates of the health costs of wildfire smoke were $1.6 m per 100,000 people per fire season, quite similar to earlier estimates for Canada and the U.S. after adjusting for inflation and the value of a statistical life used[4]. Health costs from wildfire smoke were greatest in the Gloucester landscape ($311/ha) and lowest in Casino, Kempsey and Nandewar ($13/ha). See Supplementary Table 1 for details. Our projections do not take into account changes in population density, age distribution or baseline mortality.

DATA AVAILABILITY

The data underlying the figures presented here are available on request to the corresponding author. Data underlying the analyses, figures and tables are available on request.

CODE AVAILABILITY

Code to conduct the analyses and plot the figures is available on request.

Received: 9 March 2023; Accepted: 17 July 2023;
Published online: 26 July 2023

REFERENCES

1. Xu, R. et al. Wildfires, global climate change, and human health. *N. Engl. J. Med.* **383**, 2173–81 (2020).
2. Aguilera, R., Corringham, T., Gershunov, G. & Benmahrnia, T. Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nat. Commun.* **12**, 1493 (2021).
3. Chen, G. et al. Mortality risk attributable to wildfire-related PM2·5 pollution: a global time series study in 749 locations. *Lancet Planet.* **5**, e579–587 (2021).
4. Borchers-Arriagada, N. et al. Smoke health costs change the calculus for wildfires fuel management. *Lancet Planet.* **5**, e608–619 (2021).
5. Matz, C. J. et al. Health impact analysis of PM2·5 from wildfire smoke in Canada (2013–2015, 2017–2018). *Sci. Total Environ.* **725**, 138506 (2020).
6. Fann, N. et al. The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Sci. Total. Environ.* **610–611**, 802–809 (2017).
7. Johnston, F. H. et al. Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires. *Nat. Sustain* **4**, 42–47 (2021).
8. Kelley, D. I. et al. How contemporary bioclimatic and human controls change global fire regimes. *Nat. Clim. Change* **9**, 690–696 (2019).
9. Turco, M. et al. Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nat. Commun.* **9**, 3821 (2018).
10. Clarke, H. et al. Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nat. Commun.* **13**, 7161 (2022).
11. Xie, Y., Lin, M., Decharme, B. & Seferian, R. Tripling of western US particulate pollution from wildfires in a warming climate. *Proc. Natl Acad. Sci. USA* **119**, e2111372119 (2022).
12. Mills, D. et al. Projecting age-stratified risk of exposure to inland flooding and wildfire smoke in the United States under two climate scenarios. *Environ. Health Persp.* **126**, 047007 (2018).
13. Stowell, J. D. et al. Asthma exacerbation due to climate change-induced wildfire smoke in the Western US. *Environ. Res. Lett.* **17**, 014023 (2022).
14. Penman, T. et al. Cost-effective prescribed burning solutions vary between landscapes in eastern Australia. *Front. Glob. Change* **3**, 79 (2020).
15. McColl-Gausden, S., Bennett, L., Clarke, H., Ababei, D. & Penman, T. The fuel-climate-fire conundrum: How will fire regimes change in temperate ecosystems under global climate change? *Glob. Change Biol.* **28**, 5211–5226 (2022).
16. Aparacio, B. A. et al. Evaluating priority locations and potential benefits for building a nation-wide fuel break network in Portugal. *J. Environ. Manag.* **320**, 115920 (2022).
17. Marshall, E., Dorph, A., Holyland, B., Filkov, A. & Penman, T. D. Suppression resources and their influence on containment of forest fires in Victoria. *Int. J. Wildland Fire.* **31**, 1144–1154 (2022).
18. Williamson, G., Bowman, D., Price, O., Henderson, S. & Johnston, F. A transdisciplinary approach to understanding the health effects of wildfire and prescribed smoke. *Environ. Res. Lett.* **11**, 125009 (2016).
19. Jones, B., McDermott, S., Champ, P. & Berrens, R. More smoke today for less smoke tomorrow? We need to better understand the public health benefits and costs of prescribed fire. *Int. J. Wildland Fire* **31**, 918–926 (2022).
20. Tolhurst, K., Shields, B. & Chong, D. PHOENIX: development and application of a bushfire risk-management tool. *Aust. J. Emerg. Manag.* **23**, 47–54 (2008).
21. Watson, P. J. *Fuel Load Dynamics in NSW Vegetation. Part 1: Forests and Grassy Woodlands. Report to the NSW Rural Fire Service.* (Centre for Environmental Risk Management of Bushfires, 2011).
22. Faggian, N. et al. *Final Report: An Evaluation of Fire Spread Simulators Used in Australia.* (Bureau of Meteorology, 2017).
23. Penman, T. D. et al. Effect of weather forecast errors on fire growth model projections. *Int. J. Wildland Fire* **29**, 983–994 (2020).
24. Penman, T. D. et al. Improved accuracy of wildfire simulations using fuel hazard estimates based on environmental data. *J. Environ. Manag.* **301**, 113789 (2022).
25. Clarke, H., Gibson, R., Cirulis, B., Bradstock, R. A. & Penman, T. D. Developing and testing models of the drivers of anthropogenic and lightning-caused ignition in southeastern Australia. *J. Environ. Manag.* **235**, 34–41 (2019).
26. Penman, T. D., Bradstock, R. A. & Price, O. F. Reducing wildfire risk to urban developments: simulation of cost-effective fuel treatment solutions in south eastern Australia. *Environ. Modell. Softw.* **52**, 166–175 (2014).
27. Evans, J. P. et al. Design of a regional climate modelling projection ensemble experiment - NARCliM. *Geosci. Model Dev.* **7**, 621–629 (2014).
28. Clarke, H. & Evans, J. P. Exploring the future change space for fire weather in southeast Australia. *Theor. Appl. Climatol.* **136**, 513–527 (2019).
29. Nakićenović, N. et al. *IPCC Special Report on Emissions Scenarios (SRES).* (Cambridge University Press, 2000).
30. IPCC. in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Solomon, S. D. et al.) (Cambridge University Press, 2007).
31. Collins, M. et al. in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Stocker, T. F. et al.) (Cambridge University Press, 2013).
32. IPCC. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Masson-Delmotte, V. P. et al.) (Cambridge University Press, 2021).
33. Di Virgilio, G. et al. Selecting CMIP6 GCMs for CORDEX dynamical downscaling: model performance, independence, and climate change signals. *Earth's Future* **10**, e2021EF002625 (2022).
34. Cirulis, B. et al. Quantification of inter-regional differences in risk mitigation from prescribed burning across multiple management values. *Int. J. Wildland Fire* **29**, 414–426 (2019).

ACKNOWLEDGEMENTS

We thank the New South Wales Government's Department of Planning and Environment for providing funds to support this research via the NSW Bushfire Risk Management Research Hub. We also thank the NSW Rural Fire Service and Department of Planning and Environment for providing data. H.C. receives funding from the Westpac Scholars Trust via a Westpac Research Fellowship.

AUTHOR CONTRIBUTIONS

R.B., T.P., O.P. and H.C. conceived the study. T.P. developed the risk modelling framework. B.C. carried out the fire behaviour simulations. N.B.A. contributed to the smoke health cost model. H.C. carried out the analysis and wrote the paper. All authors contributed to interpretation of the results and development of the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41612-023-00432-0.

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