New spatial analyses of Australian wildfires highlight the need for new fire, resource, and conservation policies

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Extensive and recurrent severe wildfires present complex challenges for policy makers. This is highlighted by extensive wildfires around the globe, ranging from western North America and Europe to the Amazon and Arctic, and, most recently, the 2019–2020 fires in eastern Australia. In many jurisdictions, discussions after significant losses of life, property, and vegetation are sometimes conducted in the absence of nuanced debates about key aspects of climate, land, and resource management policy. Improved insights that have significant implications for policies and management can be derived from spatial and temporal analyses of fires. Here, we demonstrate the importance of such analyses using a case study of large-scale, recurrent severe wildfires over the past two decades in the Australian state of Victoria. We overlaid the location of current and past fires with ecosystem types, land use, and conservation values. Our analyses revealed 1) the large spatial extent of current fires, 2) the extensive and frequent reburning of recently and previously fire-damaged areas, 3) the magnitude of resource loss for industries such as timber and pulplog production, and 4) major impacts on high conservation value areas and biodiversity. These analyses contain evidence to support policy reforms that alter the mode of forest management, target the protection of key natural assets including unburnt areas, manage repeatedly damaged and potentially collapsed ecosystems, and expand the conservation estate. Our mapping approach should have applicability to other environments subject to large-scale fires, although the particular details of policy reforms would be jurisdiction, ecosystem, and context specific.

wildfire extent and recurrence | sustainable forest management | forest biodiversity conservation

Fire is a key driver of ecosystem structure, condition, composition, and processes. In 2019, there were ∼20 million fire detections globally (1), with the most in the Democratic Republic of the Congo and Russia, and Australia third (∼10% of fire alerts), ahead of Brazil. Fires have long been predicted to become more severe, frequent, and widespread as a result of climate change, although they will, of course, also be influenced at local, landscape, and regional scales by factors such as fuel levels and moisture. In eastern Australia, climate change has exacerbated the extent, frequency, and severity of recent fires (2). Australia is already the most fire-prone continent (3), but assessments by the Australian Academy of Science indicate that some aspects of the current 2019–2020 wildfires are unprecedented (4). It has been estimated that these wildfires burned >12 million hectares of forests and agricultural areas across southeastern Australia (5). This is >12 times larger than the 2019 Amazon fires. More than 1 billion individual Australian animals are believed to have been killed (6), and it has been estimated that 700 species may be driven to extinction (7).

Beyond these broad-scale indicators, a deeper analysis is needed of the different vegetation types and areas under different land use that have been subject to recent and past fire. Such analysis is critical for guiding informed land management policy. We conducted such an analysis of not only the current fire but also recurrent fires for the 23 million-hectare state of Victoria, with a particular focus on forests. The majority of native forest across Victoria is under public ownership and managed by government for either wood production or as conservation reserves. The state is characterized by a wide range of ecosystem types and high levels of biodiversity in many of these ecosystems (8). We completed simple but detailed spatial and temporal analyses that intersected the location and perimeter of current and past fires with ecosystem types, land use, and conservation values. Our analysis revealed pronounced impacts on particular ecosystem types, areas of high conservation value, and the use of resources for industry. These findings, in turn, underscore an urgent need for new policies and approaches to land management that we outline later in this paper.

Results

Across Victoria, wildfires burned ∼1.5 million hectares during the 2019–2020 wildfire season. This is the largest area impacted by wildfires in Victoria since 1939 (when 3.4 million hectares burned). This season was preceded by the 2018–2019 wildfire season, where 211,713 ha was burnt (Fig. 1). The 2019–2020 wildfire is the third megafire (i.e., a fire of >1 million hectares) since 2003, with a 1.3 million-hectare fire in that year and a 1.2 million-hectare fire in 2007 (Fig. 1). Using Tukey's honest significant difference (HSD) test, we found a significant ($P < 0.05$) increase in the annual area burned across the years 2003–2020,

Significance

Discussions after significant fire-related losses of life, property, and vegetation are often conducted in the absence of nuanced debates about climate, land, and resource management policy. Here we present the results of new spatial and temporal analyses of widespread current and previous fires in the Australian state of Victoria that highlight the need for major changes in policies associated with fire and land management. We found compelling evidence to support policy reforms that aim to reduce megafires, alter the mode of forest management, target the protection of key natural assets including unburnt areas, manage repeatedly damaged and potentially collapsed ecosystems, and expand the conservation estate. Our approach should have wide applicability to other jurisdictions confronting threats from widespread, recurrent wildfires.

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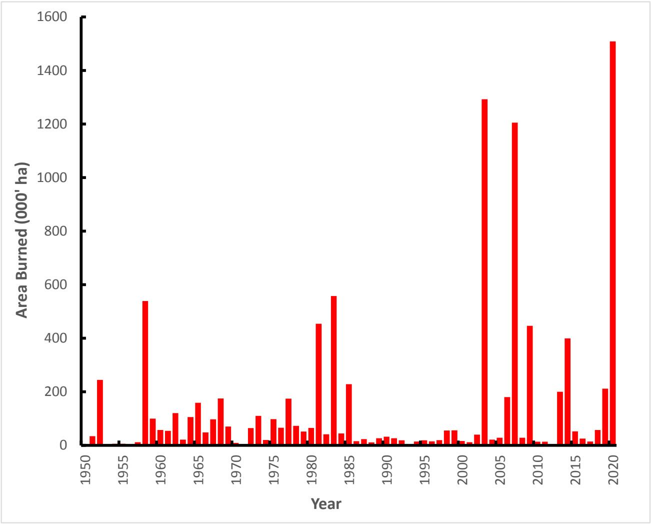

Fig. 1. Area burned across Victoria from 1950 to 2020, showing a significant ($P < 0.05$) increase of annual areas burned after 2000.

compared with annual areas burned over the preceding 52 y (*SI Appendix*, Table S1). This significant increase is a result of the 2003–2020 period featuring three large megafires (>1 million hectares in size) and no such fires in the previous period (1950–2002).

Analyses of fire frequency in Victoria revealed that, since 1995, many areas have experienced multiple wildfires within short timeframes (e.g., 5 y to 6 y; *SI Appendix*, Tables S2–S4). Of the 1.5 million hectares burned during the 2019–2020 fire season, 600,109 ha have burned twice, and 112,957 ha have burned three times over the past 25 y (Fig. 2). Similarly, there was major wildfire activity during March 2019, where >70% of the 211,691 ha affected had previously burned in the past 25 y, with 11% (22,325 ha) burned three times. Around 50% of the overall area burned for the combined wildfire seasons of 2018–2019 and 2019–2020 had been previously burned by wildfires occurring within the past 25 y. Fires are recurring at far shorter than natural return intervals, such as in forest types that should burn no more frequently than every 75 y to 150 y on average (e.g., the Mountain Ash [*Eucalyptus regnans*] forest ecosystem) (9). Ecosystems therefore have too little time to recover before being reburned.

Some ecosystem types (classified as Ecological Vegetation Class [EVC] groups in Victoria) have been heavily fire affected (*SI Appendix*, Table S3). For example, almost 91% (115,000 ha) of the total extent of Snowgum (*Eucalyptus pauciflora*) forest has been burnt since 1995, with 40% burned by two or more fires. Of the Wet and Damp Forest EVC Group (that includes stands of Mountain Ash), 805,215 ha (65%) have been burnt, with 22% burned multiple times in 25 y (*SI Appendix*, Fig. S1).

Areas of high conservation value for biodiversity have been extensively disturbed. Approximately 57% of the top 10% most important areas for Victoria's 70 forest-dependent threatened species have been burnt in the current wildfires (Fig. 3), with 15% burned twice or more in the past 25 y.

Fires have differentially affected areas subject to different land uses (*SI Appendix*, Fig. S2 and Table S4). The most heavily impacted land use type is wood production native forest, with 63% (2.0 million hectares) of the total timber estate burned since 1995. Of this, 18% (607,389 ha) has burned two or more times. Of the area proposed for logging in the East Gippsland region of Victoria in the next 5 y under the Victorian Government's Timber Release Plan (10), 59% has recently been burned. This equates to ∼28% of all planned logging areas throughout the state of Victoria. Protected areas have also been impacted, with 44% (1.9 million hectares) of the total conservation estate burned since 1995 and 505,943 ha burned multiple times. Using Tukey's HSD test, we found that the annual area burned between 2003 and 2020 has increased significantly for both conservation areas ($P < 0.05$) and wood production native forests ($P < 0.05$) since 2003, compared with the previous 52 y (*SI Appendix*, Table S1).

Discussion

New Policies to Respond to Unprecedented Fires. Our spatiotemporal analyses provide a compelling case for climate, fire, and

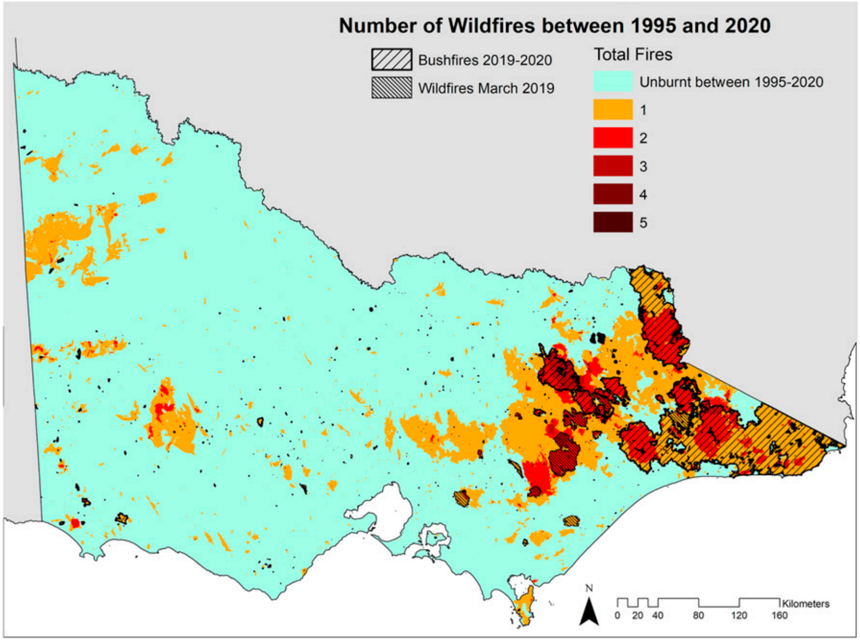

Fig. 2. Extent and frequency of wildfires across the state of Victoria with the outlines of the wildfires that burned during 2019 and 2020.

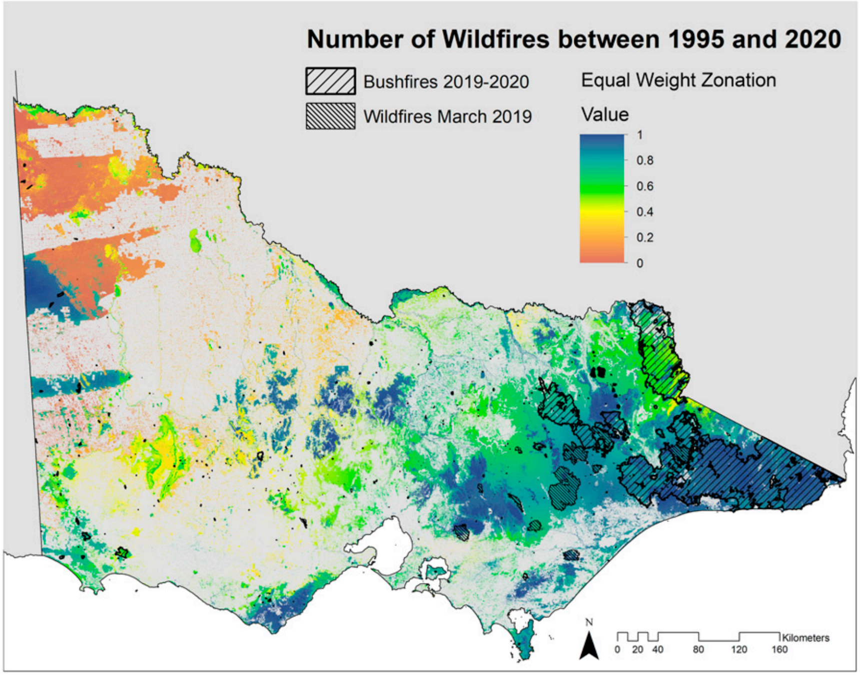

Fig. 3. Priority areas for 70 forest-dependent species across Victoria showing areas burned during March 2019 and the period between November 2019 and 12 January 2020 (8).

land management policy reform. Reform is needed because of 1) the large spatial extent of current fires (including megafires), 2) the extensive and frequent reburning of recently and previously fire-damaged areas, 3) the magnitude of resource loss for timber production and other forest-based industries, and 4) major impacts on high conservation value areas and biodiversity. More-effective and immediate global and national-scale actions to ameliorate climate change are essential given that climate and weather are major drivers of fire risk and behavior (3). At smaller scales, there is a need for land management reform, especially in areas distant from human settlements. Below, we describe some of the policy and practice changes that are needed.

There are major policy implications of the spatial extent of wildfires. Widespread wildfires (so-called megafires) highlight the need to tackle climate change. Beyond climate policies, there is a need to reexamine management practices that contribute to fire proneness at landscape scales and within areas under different land uses. Our analyses for Victoria revealed that a significantly greater proportion of wood production forest has burned in the current fires (and has reburned in the past 25 y) than conservation areas. This is consistent with research in a wide range of ecosystems, and, particularly, moist forests, which indicates that logging and the creation of young flammable stands of trees can contribute to fire risk (11, 12). This suggests a need for policies to expand the area of old growth (which is less prone to high severity fire) (11) and limit the extent of spatial contagion of megafires. There is also a need to better protect rivers, creeks, and lakes, given the impacts of fire on water quality for biodiversity (see ref. 13).

Our analyses revealed that extensive areas have been burnt repeatedly (up to three times) in 25 y (Fig. 2), with the interval between fires as short as 5 y to 6 y in some vegetation types, like those dominated by Wet and Damp EVC groups. This is many decades shorter than is the typical mean fire return interval of 75 y to 150 y for such vegetation types (9). Demands for more burning (such as through additional prescribed or hazard reduction fires) in some ecosystems are misguided, especially given that so much vegetation has already burned, and that some ecosystems (such as those dominated by Mountain Ash forest and Snowgum woodland) need less rather than more fire if they are to recover. Further disturbances can impair biodiversity recovery [including species that might have otherwise persisted in fire-damaged areas (14)]. In addition, species richness of birds can be reduced by ∼10% with each additional fire in a given ecosystem (15). Similarly, expanding the proportion of a landscape that is burnt will drive down mammal and bird species richness (16). Conversely, some management activities in burnt areas are critical, particularly the control of invasive herbivores (such as introduced deer) and carnivores (e.g., feral cat) that are attracted to fire-damaged locations. Recurrent wildfire at short return intervals can eliminate key forest age classes such as old growth, deplete critical elements of stand structure such as large old trees (17), and impair resprouting by some species of fire-tolerant tree species (18). It also can trigger ecosystem collapse with replacement by different (novel) ecosystems (19) that have impaired service values. As an example, recurrent fire at short interfire intervals could result in the loss of ecosystems such as those dominated by Mountain Ash and their replacement by *Acacia* spp. woodlands that would store less carbon, generate less water for human consumption, and fail to provide suitable habitat for a wide range of species (20). It remains unclear how novel ecosystems might be managed and whether restoration of previous vegetation is required, or even possible. Where it can be foreseen that restoration is not possible after successive wildfires, contingency preparation will be required. For example, it may be prudent to establish ex situ stores of seeds to assist the restoration of prefire vegetation (such as the overstory trees killed by recurrent fire). A key strategy in environments at risk of transformation should be to retain residual elements of previous ecosystems (e.g., old trees and habitat patches) that can lifeboat species and facilitate their persistence in new ecosystems (21).

The spatial extent of fires has implications for land uses such as wood production, given that extensive amounts of existing timber resources have been burnt. The large amount of native forest in Victoria dedicated to logging that is now burnt means that native forest-dependent logging industries will no longer be sustainable or economically and ecologically tenable. Such large losses indicate a need to revise down sustained timber and pulplog yields; otherwise, unburnt wood production forests will be quickly overcut. The high frequency of reburning also threatens the viability of forest industries in the medium to long term. This is, in part, because fires will destroy tree crops before they reach an age that can yield logs for sawn timber. For example, the nominal rotation time for logging in Mountain Ash forests is 80 y (22), but the frequency of reburning in such forest types will preclude stands of trees in this ecosystem reaching an age sufficient to provide sawlogs. Proposals to shift logging into unburnt areas currently under other land use classes (such as conservation) (e.g., ref. 23) are unacceptable. This is because of the importance of the remaining unburnt areas for conserving biodiversity (as quantified by analyses of fire impacts on high conservation value areas). The increasing rarity of long-unburnt areas means they should be the focus of targeted protection including focused fire suppression efforts [as occurred for small, relict stands of the iconic Wollemi Pine (*Wollemia nobilis*) west of Sydney (24)]. Moreover, there is a strong case for expanding current reserve systems to increase the chance of them supporting some unburnt areas in the future. The large spatial extent and high frequency of wildfires, together with the need to better protect unburnt areas, clearly indicate that, in highly fire-prone environments such as native forests in Victoria, there is an increasing need to shift wood production into tree plantations. Concentrating wood production in geographically dispersed plantations may reduce the risk of loss of timber and pulplog resources. In addition, stands of plantation trees can be harvested for sawlogs on a shorter rotation (20 y to 25 y) than from native forests, increasing the probability of extracting a crop before wildfire occurs.

Conclusions

Our overview of current and recent past fires in Victoria, southeastern Australia, based on spatiotemporal analyses, provides compelling evidence of the need for new fire, resource management, and conservation policies. Such extensive and recurrent severe wildfires may be a forerunner for altered fire conditions elsewhere in the world (25), and our mapping-based approach to evidence-based policy reform may have value in guiding responses in other environments subject to widespread conflagrations.

Materials and Methods

We used a fire history dataset that represented the spatial extent of the last fires recorded from 2019, primarily on public land across Victoria (26). This dataset stores details of the last time an area was known to be burnt by wildfire and represents a consecutive overlay of all fires recorded since 1900. The data only showed the extent of past fires, but not severity. This dataset did not feature the extent of the wildfires burning across Victoria during the 2019–2020 wildfire season. We extracted the extent of these fires from the Emergency Victoria database (27). We sourced land use data from the Australian Collaborative Land Use and Management Program (ACLUMP) to inform our land tenure analysis (28) (*SI Appendix*, Fig. S2). ACLUMP is a nationally agreed classification system for land use information and provides a monitoring and evaluation framework, consisting of a three-tiered hierarchical structure. However, limitations of ACLUMP include the absence of land use change over a given period of time, the coarse scale of the datasets (1:2,000,000), and relative SEs across agricultural land use (28). We cross-validated the ACLUMP dataset with regionally specific land use maps and vegetation extent obtained through satellite data, along with Forest Management Zones and Collaborative Australian Protected Area Database protected area boundaries (29). We previously corrected errors in spatial data where we detected them (8). We sourced Ecological Vegetation Group datasets from the Native Vegetation - Modeled 2005 Ecological Vegetation Classes dataset (30). The EVC Groups dataset was developed by the Victorian Government to categorize the landscape into native woody cover, native grassy cover, and native wetland cover. We used the EVC Groups category, which covered 20 vegetation broad native vegetation types, including Wet and Damp Forests, Rainforests, Dry Forests, and Mallee EVC Groups (*SI Appendix*, Fig. S1).

We derived the areas for the top 10% for 70 forest-dependent threatened species from Taylor and Lindenmayer (8). That study generated a series of Zonation maps (31) that located areas of priority for 70 forest-dependent threatened species across Victoria, based on unpublished Habitat Distribution Models for the Victorian Environment Assessment Council in its assessment of biodiversity values across Victoria (32) (see appendix S12 of ref. 8). The species not included were those not dependent on native forests or those found to inhabit other habitat types in addition to native forests (32). The Zonation analysis was generated using an equal weight for all species.

Zonation produces a hierarchical ranking of multiple species habitat distribution models over the landscape using a series of algorithms. Zonation's "core area" algorithm was used to allocate a conservation value to each cell across the landscape based on the relative suitability of a cell for each species and the proportion of the remaining habitat for each species that the cell represents. In this way, zonation ranked each cell in the landscape according to how "irreplaceable" it was for achieving representation of the suitable habitat for each species (31).

Spatial Analysis. Our analysis consisted of assessing the extent of areas burned by wildfire between the years 1995 and 2020. This latter date immediately followed a period of intense fire activity across the state of Victoria (27). We selected 1995 as the start year because it immediately preceded the commencement of the Millennium Drought, where much of southern Australia experienced a prolonged period of dry conditions from late 1996 to mid-2010 (33). We combined the extent of wildfire areas burned between 1995 and 2020. We identified areas burnt multiple times over the analysis period. We also examined areas burnt from 1950 forward. We tested for any significant change ($P < 0.05$) for the period following the first megafire (2003) compared with the preceding period dating back to 1950. We used a Tukey's HSD test to test for statistical significance.

We assessed and calculated areas burnt across ACLUMP land tenures, EVC Groups, and the top-ranking 10% Zonation-generated priority areas (8) for the 70 forest-dependent threatened species identified in the Victorian Environment Assessment Council assessment of biodiversity values across Victoria (32) (see appendix S12 of ref. 8). We also assessed the number of times each land tenure category, EVC Group, and top-ranking zonation areas had been burnt between 1995 and 2020. We assessed for any significant change in annual area burnt specifically across conservation reserve and state forest land tenure, using Tukey's HSD test.

Data Availability. All data are in the paper and *SI Appendix*.

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