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The severity and extent of the Australia 2019–20 *Eucalyptus* forest fires are not the legacy of forest management

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The 2019–20 wildfires in eastern Australia presented a globally important opportunity to evaluate the respective roles of climatic drivers and natural and anthropogenic disturbances in causing high-severity fires. Here, we show the overwhelming dominance of fire weather in causing complete scorch or consumption of forest canopies in natural and plantation forests in three regions across the geographic range of these fires. Sampling 32% (2.35 Mha) of the area burnt we found that >44% of the native forests suffered severe canopy damage. Past logging and wildfire disturbance in natural forests had a very low effect on severe canopy damage, reflecting the limited extent logged in the last 25 years (4.5% in eastern Victoria, 5.3% in southern New South Wales (NSW) and 7.8% in northern NSW). The most important variables determining severe canopy damage were broad spatial factors (mostly topographic) followed by fire weather. Timber plantations affected by fire were concentrated in NSW and 26% were burnt by the fires and >70% of the NSW plantations suffered severe canopy damage showing that this intensive means of wood production is extremely vulnerable to wildfire. The massive geographic scale and severity of these Australian fires is best explained by extrinsic factors: an historically anomalous drought coupled with strong, hot dry westerly winds that caused uninterrupted, and often dangerous, fire weather over the entire fire season.

Wildfire is an ancient natural ecological disturbance that biotas have evolved specialized adaptations and strategies to resist and recover from[1]. There is concern that climate change is diminishing the capacity of fire-adapted vegetation to recover following wildfire[2,3]. Climate change can increase the frequency and severity of wildfires due to hotter and drier conditions[4] which also reduces the post-fire recovery due to lower vegetation survival, recruitment and growth[3]. Climate-driven changes to historical fire regimes may lead to broad-scale ecological transformations including ecosystem replacement, reduced carbon storage and changed nutrient and hydrological cycles[5,6]. These ecologically transformative fires often involve complex interactions between different types of disturbances that potentially increase landscape flammability and fire occurrence[6]. In Australia, for instance, it has been posited that logging has rendered landscapes more prone to severe fires, compounding the effect of climate change and that intensively managed timber plantations are potentially a less fire-prone means of wood production[7]. Here, we show that neither the severity nor extent of the geographically enormous east coast 2019–20 fires are attributable to logging history in native *Eucalyptus* forests and that plantations are extremely vulnerable to complete canopy scorch or consumption of forest canopies ('severe canopy damage'). Anomalous fuel dryness, combined with extended periods of extreme fire weather are by the far the most dominant, and parsimonious, explanation for the vast extent and severity of impacts of these fires and, in particular, more than past forestry practices.

Wildfires are a common natural disturbance in Australian *Eucalyptus* forests to which the flora and fauna are highly adapted[8]. *Eucalyptus* forests are renowned for their tolerance of frequent fires because of post-fire resprouting and prolific seedling establishment[9]. Broadly, there are two main *Eucalyptus* forest types: wet and dry. Wet *Eucalyptus* occur in the most productive landscape settings and can support tall forests (>60 m) with dense broadleaf shrub or tree understorey. Fire regimes in wet forests are characterized by infrequent (~50 yr) fires which vary in severity from stand-replacing high-severity fires to low-severity surface fires with negligible demographic effects[8]. Fuel is abundant in wet forests and fuel moisture limits fire occurrence and extent[10]. Dry *Eucalyptus* forests are of lower stature (>20 m) with open understories typically made up of low (<4 m) sclerophyllous shrubs. Although available to burn every fire season, dry forests are fuel limited and generally support frequent (~10 yr) low-severity surface fires[11] but intense crown fires can occur under extreme fire conditions[8].

Most *Eucalyptus* species have well-developed adaptations to resist and recover (vegetatively and/or sexually) from fire, although there are a few obligate-seeder species that are typically wet forest specialists[9]. Frequent high-severity fires can cause a substantial reduction in tree density in forests dominated by both resprouting and obligate-seeding species[12–14]. For instance, three fires in quick succession in the early twenty-first century caused the demographic collapse of an obligate-seeder-dominated *Eucalyptus* forest[15].

The 2019–20 bushfire season in eastern Australia was quantitatively and qualitatively different from all other known fire seasons that preceded it[16]. The fire season was prolonged, starting in northern New South Wales (NSW) in August, much earlier than usual because of a historically extreme drought[17]. The fires, often

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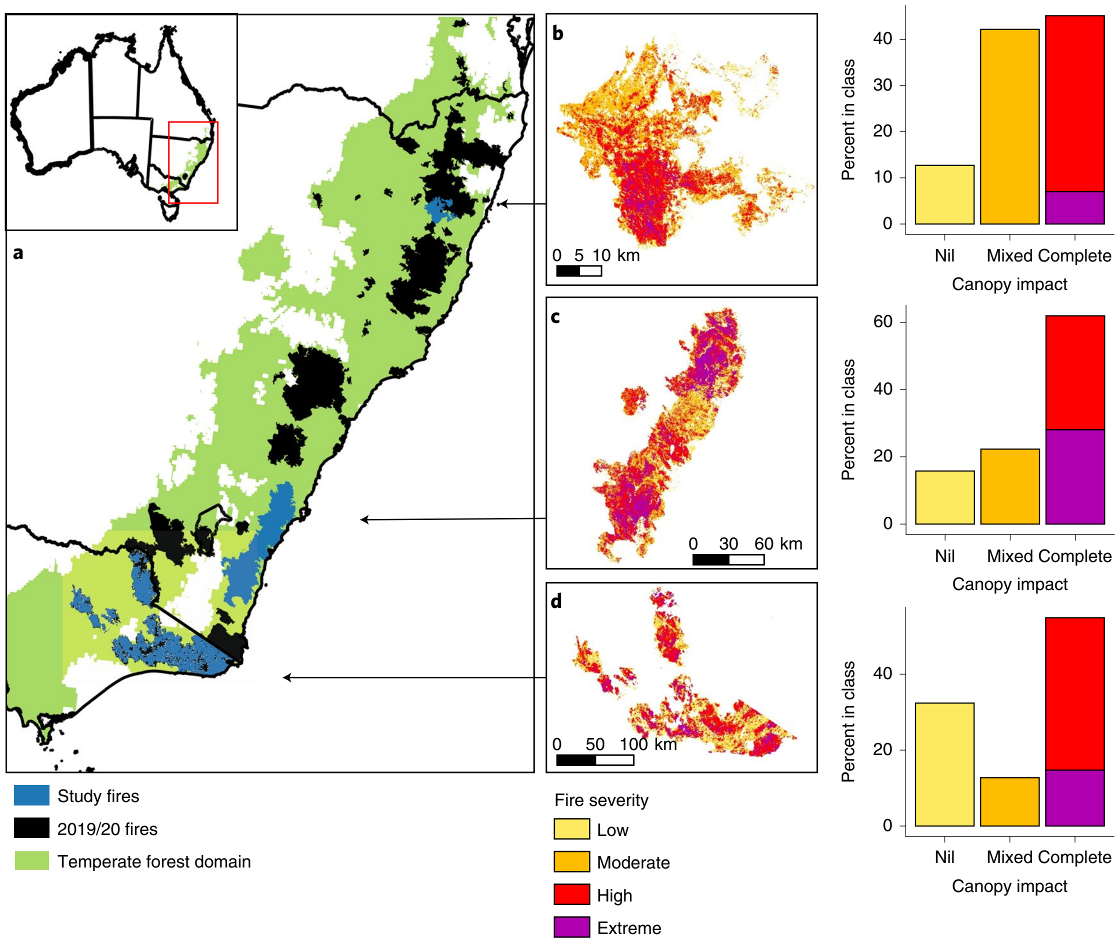

Fig. 1 | Geographic extent of the 2019–20 east coast Australian fires that burnt in the temperate *Eucalyptus* forest domain. a, The three study areas across the geographic range of the fires are indicated in blue. **b–d**, Insets show the geographic pattern and frequency distribution of fire severity across the three study areas (northern NSW (**b**), southern NSW (**c**) and eastern Victoria (**d**)), where high- and extreme-severity, respectively, relate to complete canopy scorch and consumption, and moderate- and low-severity relate to patchy or undamaged forest canopies.

driven by strong hot westerly winds, burnt >7 Mha, extending from the subtropics to temperate zone, including ~18% of the total Australian coverage of *Eucalyptus* forests[16]. Many of the fires exhibited periods of extreme fire behaviour, including >30 pyrocumulonimbus events or fire-created thunderstorms, doubling the previous Australian record of these storms in one fire season[5,18]. Greenhouse gas emissions from the fires were globally anomalous[19] and included stratospheric smoke transported around the southern hemisphere[20]. Over a 5-month period, the east coast of Australia, where most of the Australian population resides, was exposed to multiple days of smoke pollution that exceeded national air quality standards[21,22]. The fires had substantial biodiversity impacts[23]. Nonetheless, the number of human fatalities and properties destroyed was not historically anomalous.

Globally there is intense interest in the relative contribution of climate drivers and land management legacies on the scale and severity of the wildfires[24–30]. In the case of the Australian 2019–20 fires, several authors have drawn attention to the widespread and anomalous fuel dryness that predisposed the landscape to burn[31,32]. This dryness has been associated with unusual climatic conditions, possibly associated with climate change[33]. By contrast, others have proposed, in addition to extreme dryness, the legacy effects of land management. One view is that the scale and intensity of the fires was substantially due to insufficient fuel management[34]. Conversely, it has been asserted that the widespread high-severity fires, causing canopy consumption or complete canopy scorch, were associated with past logging history[7,35]. This latter argument is based on the 'landscape trap' hypothesis where dense regrowth that establishes in the first few decades after logging of a stand-replacing fire is considered more flammable than older stands because of dense canopies that are close to heavy surface fuels and drier microclimates[36].

Prior analyses of fire severity have shown that 20–70-yr-old post-fire regrowth in wet *Eucalyptus regnans* forests is more prone to severe canopy damage than younger or older stands[37], although, in ecologically similar montane wet *E. delegatensis* forests in Victoria, disturbance history was shown to be a relatively small effect on fire severity when compared to the influence of fire weather[24]. To further explore the relevance of the landscape trap hypothesis and the putative effect of recent forest harvest and wildfire disturbances, we undertook a geospatial analysis for three large fires in eastern Victoria (1.3 Mha), southern NSW (923,000 ha) and northern NSW (119,000 ha) that spanned the geographic range of the Australian fires. The total area sampled (2.35 Mha) included 32% of the area burned on the east coast by the 2019–20 bushfires (Fig. 1). For these areas we sourced fire-severity mapping from NSW and Victorian government data (Data availability) on the basis of RandomForest statistical classification of satellite-based fire-severity metrics[38,39] defining three fire-severity categories in terms of canopy impact: nil, surface-only fires (the 'low' satellite severity class); mixed (the

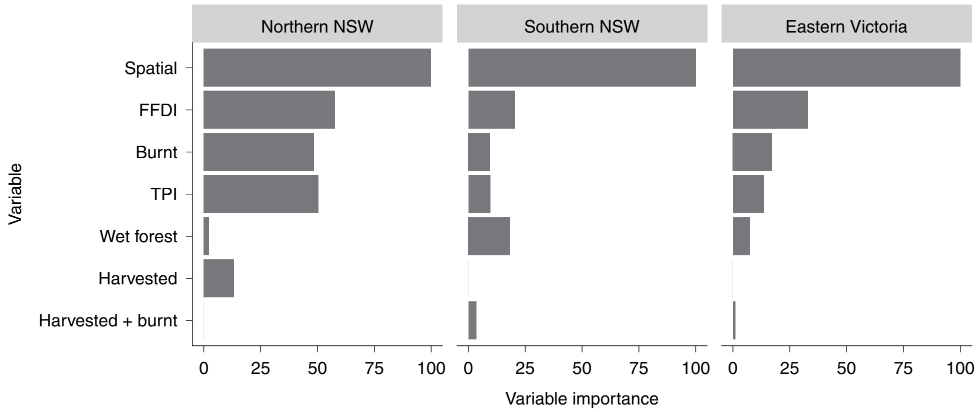

Fig. 2 | Relative importance of variable in driving fire severity. Scaled model variable importance (in units of absolute value of the *t*-statistic) for the global model (severity ≈ forest history + FFDI + vegetation + TPI + spatial) across the three study sites was calculated for each parameter[63]. The variables used in the modelling are as follows: spatial, spatially smoothed model residuals controlling for spatial autocorrelation[61]; FFDI, McArthur Forest Fire Danger Index at approximate time of burning; burnt, whether the forests were burnt <25 yr ago; TPI, topographic position index calculated with a 250-m window according to De Reu et al.[64]; wet forest, allocating land cover to wet *Eucalyptus* forest; harvested, harvested within last 25 yr; harvested + burnt, harvested and burnt within last 25 yr.

'moderate' satellite severity class); and complete (the 'high' and 'extreme' satellite severity classes; Methods). Specifically, we tested whether 'high' and 'extreme' satellite severity classes, that cause complete canopy scorch or consumption ('severe canopy damage'), relative to unburnt canopy (nil) was predominantly influenced by fire weather conditions, past land use (for example, logging and fire history) or other landscape characteristics such as terrain and vegetation, using statistical techniques to control for spatial autocorrelation.

Our analysis advances previous geospatial analyses because we consider the effect of recent (<25 yr) native forest logging, past fire disturbance and their interactions in both wet and dry *Eucalyptus* forests. We include in our analyses the effects of fire weather and terrain (Methods). To contextualize our study of fire severity in native forests used for timber harvesting, we also compare the fire severity in forestry plantation (predominately *Pinus radiata*) and native production forests burned by the 2019–20 fires in NSW.

Results and discussion

Predictors of severe canopy damage. The three study areas were centred on *Eucalyptus* forests, with different mixtures of wet and dry forest types: northern NSW (44% wet and 42% dry); southern NSW (39% wet and 36% dry) and eastern Victoria (2% wet and 91% dry). Across the three regions >44% of the burnt areas were affected by severe canopy-damaging fire (combining high- and extreme-severity classes[38,39]). Yet, the extent of past logging in the last 25 yr was much lower (4.5% in eastern Victoria, 5.3 in southern NSW and 7.8% in northern NSW) suggesting no connection between fire severity and logging. Our statistical analysis supported this disconnection showing the drivers of severe canopy damage that broadly were the same across the three study sites (Fig. 2); in all cases, residual spatial variance was the most important variable in the model, reflecting broad spatial patterns of fire severity not captured by the other variables, followed in importance by fire weather (Forest Fire Danger Index, FFDI). Recent harvest status, in combination or separate to recent burning, was universally ranked low in importance as a driver of fire severity.

Akaike information criterion (AIC)-based model rankings (Supplementary Tables 1–3) show that the global (eastern Victoria and southern NSW) or global without FFDI (northern NSW) models ranked highest across the three study regions, confirming the relevance of multiple variables in driving fire severity. Fire weather clearly affects fire severity, regardless of disturbance history across the three study areas (Fig. 3). Fire severity was found to have a relationship with topographic position, with the canopy-damaging categories found to be associated with high topographic position index (TPI) (ridges) and lower severity with valleys (Extended Data Fig. 1).

Our findings concord with a detailed geospatial analysis of high fire severity in dry *Eucalyptus* forests in NSW which also found that an index of spatial autocorrelation was the most important explanatory predictor, followed by fire weather[40]. Our spatial autocorrelation factor is probably reflecting very rapid expansion of fire under extreme fire conditions ('fire runs') given that this overwrites finer grained terrain variables such as vegetation pattern and topography. For instance, under extreme fire weather conditions (FFDI > 100) during the Black Saturday fires in 2009 there was strong autocorrelation of crown fire severity at distance up to 10 km (ref. [41]). In our study, more detailed analysis of the effect of this spatial contagion was not possible due to the absence of fine-scale and temporally precise mapping and of growth of the fire front.

Overall, while undisturbed forests are slightly less likely to experience high-severity fires than are disturbed forests, marginal effects plots of forest history (burning, harvesting or both) and FFDI showed inconsistent effects of recent harvesting and burning on probability of severe fire. Other landscape ecology analyses of fire severity in *Eucalyptus* forests have also found that fire weather is the primary determinant of crown-damaging fires relative to other environmental predictors, such as previous fires or logging[24,40–44]. A good example of this is the study by Taylor et al.[44] who demonstrated that fire weather had a dominant statistical effect in crown scorch or consumption in thinned and unthinned wet and dry *Eucalyptus* forests in Victoria.

In the western United States, fire weather variables are also dominant predictors of crown fires, although live fuel biomass has also been found to be important, especially in dry forest types. For example, the macro-ecology analysis and review of Parks et al.[26] across all ecoregions of the western United States suggested that the abundance of live fuel was the strongest and most consistent predictor of high-severity fire, with various combinations of fire weather, climate and topography as important subsidiary factors but fire weather was the most important variable in five of the 19 study ecoregions. Lydersen et al.[45] highlighted the effectiveness of managing live fuel to reduce fire severity. Interventions such as thinning of

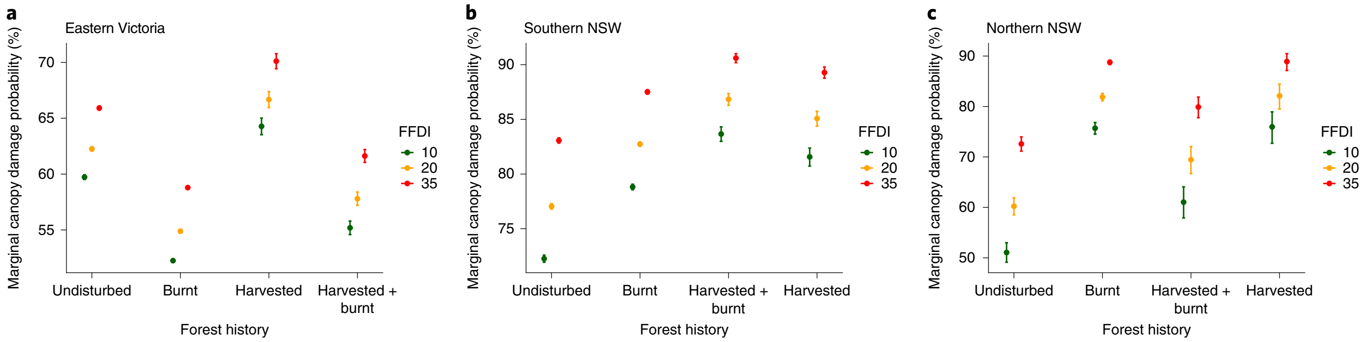

Fig. 3 | Marginal effects of forest history on fire severity. a–c, Marginal effect plots of forest history (harvesting and burning) and FFDI for the three study sites: eastern Victoria (**a**), southern NSW (**b**) and northern NSW (**c**).

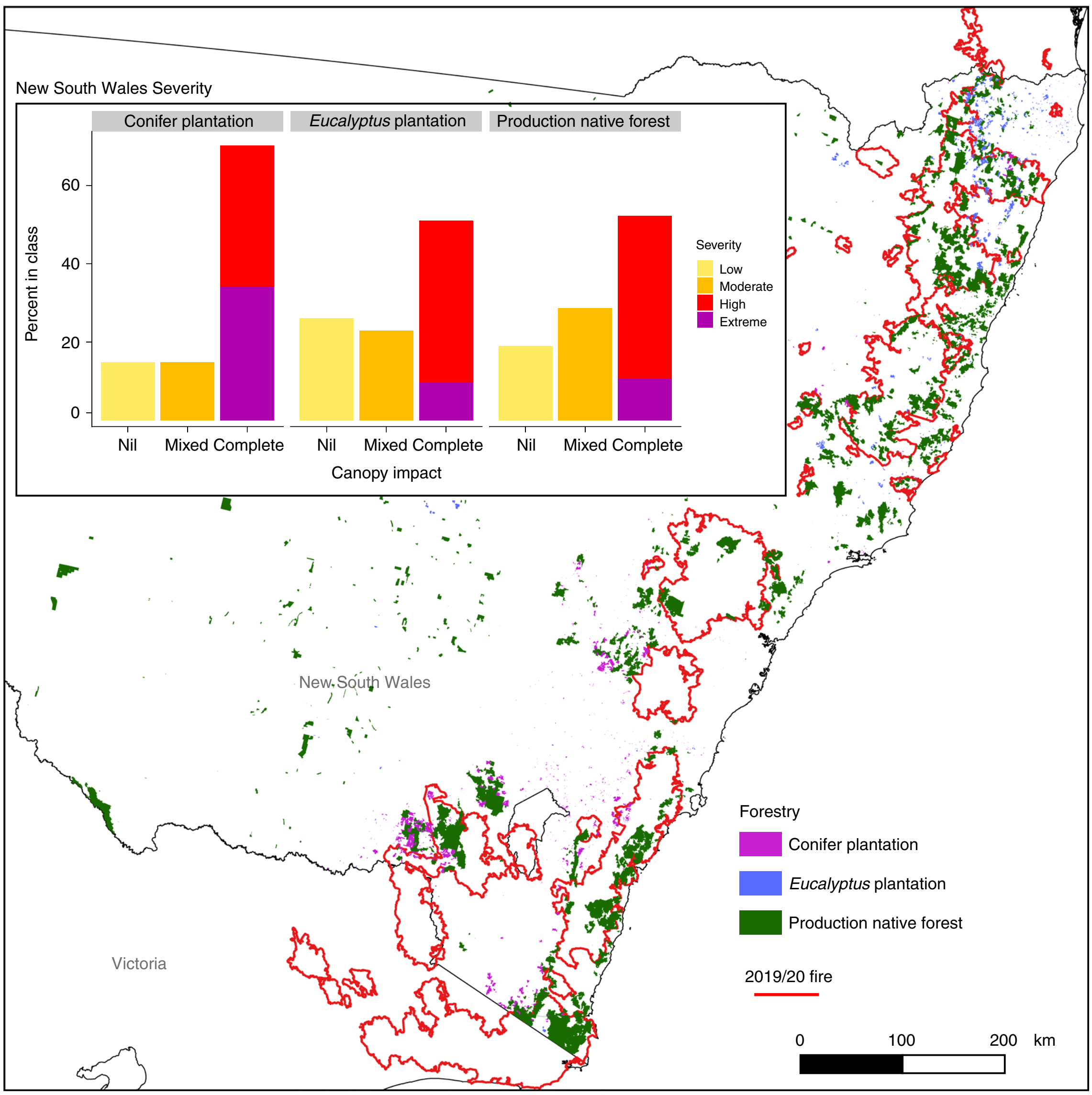

Fig. 4 | Map of plantations and 2019/20 fire boundaries, with relative proportion of canopy impact classes. Map of conifer plantation, *Eucalyptus* plantation and production native forest areas in NSW in relation to 2019/20 fire boundaries. Inset shows relative proportion of fire canopy impact classes in the three forest types for areas burnt in the 2019/20 fire season. Plantation data are not available for eastern Victoria.

forests, prescribed burning (or both) or allowing fires to burn under moderate fire weather conditions, can reduce the severity of fires compared to untreated areas.

We have shown that extreme fire weather conditions and topography have a much greater influence compared to disturbance history in causing severe fires. Nonetheless, our findings show

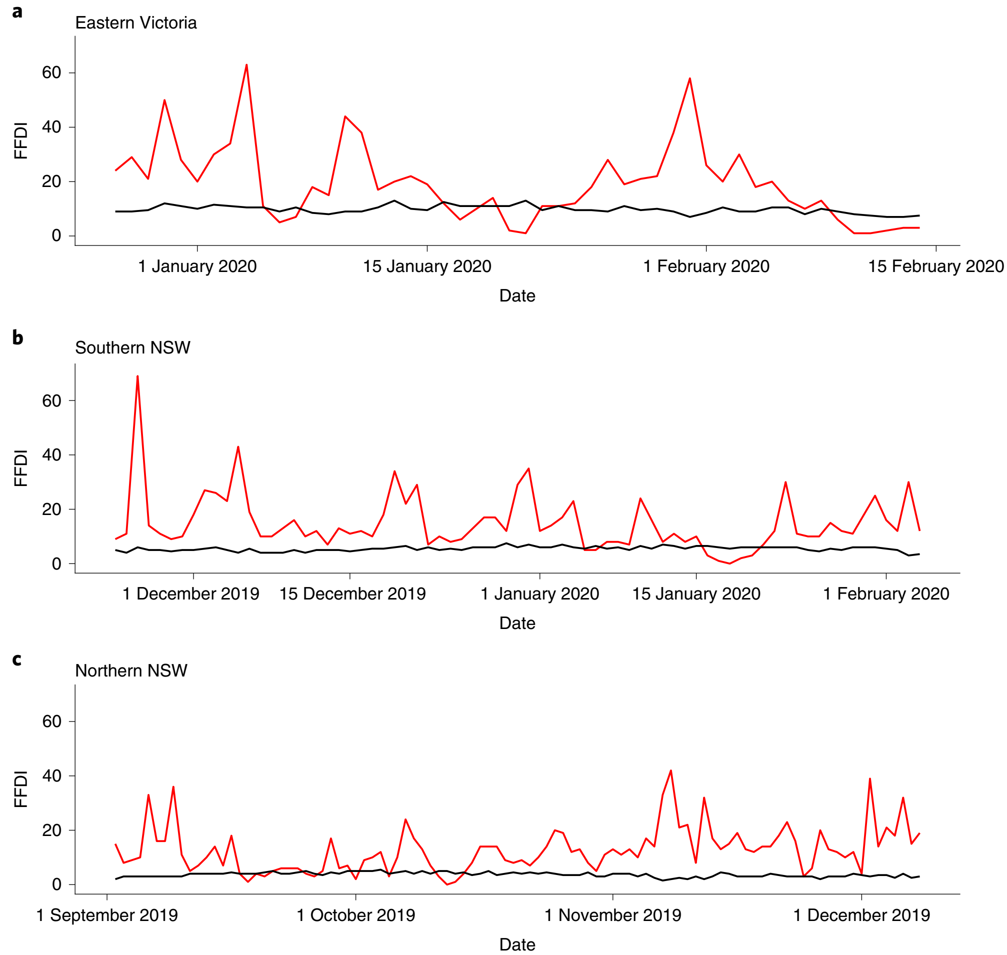

Fig. 5 | Daily McArthur Forest Fire Danger Index (FFDI) for the three case-study fire areas. a–c, Eastern Victoria (**a**), southern NSW (**b**) and northern NSW (**c**) shown by the red line—with 30-yr median FFDI for the same days of year shown by the black line.

complex interactive effects amongst disturbance history and ecoregion under more moderate fire weather (Fig. 3). This suggests that the 'landscape trap' idea, which places primary emphasis on intrinsic fire hazard, is strongly contingent on extrinsic climatic factors. This contingency on extreme fire weather highlights an unresolved global management challenge in mitigating impacts of extreme fires under a rapidly warming and drying climate[19,29]. Fuel loads are likely to become less important than climate drivers in determining fire extent and severity, making it increasingly difficult, if not impossible, to maintain large areas of unburnt forest in a low-fuel state sufficient to impede rapid fire spread and thus limit the extent, frequency and severity of future forest fires.

In addition to the large area of native forest impacted, over one-quarter (26%) of NSW commercial forestry plantations were burned, with non-native conifer plantations suffering a greater proportion (70%) of severe canopy damage than *Eucalyptus* plantations (51%) or native production forests (52%) (Fig. 4). The higher flammability of conifer plantations than *Eucalyptus* plantations or native forests is possibly due to higher live fuel load and density in *Pinus* tree crowns than *Eucalyptus*, although this requires further investigation. The vulnerability of both *Eucalyptus* and conifer plantations to severe crown fires is supported with studies from Chile and Portugal reporting high-severity fires in *Pinus* and *Eucalyptus* plantations[46,47].

Several important features emerge from our analysis. First, the most parsimonious explanation for the huge extent and high severity of the 2019–20 fires lies with the preceding three consecutive, anomalously dry winters that were unprecedented in the previous 100 yr, combined with sustained hot windy weather during the fire season[17]. The drought primed the landscape to burn because of vast areas of tinder-dry forests, with leaf litter dryness levels at a 30-yr low in many areas[31]. In all three of our study regions, forest fire danger indices were well above the historic median value in summer for long periods (Fig. 5). Notable features of the 2019–20 fire season were limited rainfall and long periods of elevated fire weather conditions that hampered control operations and promoted rate of fire spread. Second, while our study provides some support for the concept that regenerating *Eucalyptus* forests can increase the risk of fire severity[36,37,48], we show that these effects are regionally variable and are completely subsumed by other landscape-scale variables, particularly fire weather and topography. The importance of fire weather in controlling canopy damage in *Eucalyptus* forests has been reported in many other landscape analyses[24,40–44,49]. Third, the high proportion of high-severity fires in forest plantations counteracts the suggestion that this form of wood production can be used as a way of avoiding any purported landscape fire hazards created by logging native forest[7,35]. Finally, mitigating future risks presented by such massive fires in a rapidly changing climate remains a profound policy, management and scientific challenge[19,29].

Methods

Forestry historical and geographic context. In our analysis we define logging as the harvesting of native tree species, predominantly *Eucalyptus* and *Corymbia*, from native forests. Typically, this involves localized clearfelling or felling forest in patches and burning of forest debris, with differences between regions and wet and dry forest types. Native production forests are a specific type of government land tenure set aside for commercial logging. Logging also occurs on private land, primarily in northern NSW and Tasmania. Wood production in the study regions also occurs in intensively managed plantations, predominantly non-native *Pinus* species in southern NSW. Below, we briefly provide an historical context and description for our three study regions.

Historical context. *Native forest silviculture.* Before colonization in 1788, traditional owners actively managed large areas of Australia's forested landscapes[50]. After colonization, native forests were extensively exploited for commercial tree species, degraded by mining and large areas converted to agriculture. Between the 1880s and the 1920s, forest conditions were sufficiently dire for various state parliaments to legislate to protect forests and place rudimentary regulation on harvesting and clearing, often against strong opposition from agricultural interests[51]. Following World War II, logging became more regulated and increased to meet the timber demands of a growing human population. Native forests were subject to more intensive management practices, such as clearfelling and conversion to plantations. A rising environmental consciousness through the 1980s and 1990s led to improved environmental standards and greater protection of forests for wildlife and other forest values, including increased areas in conservation reserves[52]. This trend accelerated in the 2000s and volumes of timber harvested from native forests fell dramatically between 2005 and 2015[53].

Plantations. Planting of softwood trees for timber production began in the late 1800s and expanded from the 1920s, mostly through converting poor-quality, mixed-species native forests. These plantations consist of ~1 Mha of softwoods established mainly through public investment on state forest lands between 1960 and 1990. In the late 1980s, most states banned the clearing of native forests for plantations and, since the mid-1990s, almost all plantations have established on previously cleared land, usually farmland[54]. Between 1990 and 2010, 1 Mha of *Eucalyptus* has been established primarily through commercial schemes. Plantations are intensively management (cultivation, weed control and fertilizing) optimized productivity.

Forest harvesting in the three study areas. *Eastern Victoria.* In East Gippsland there are 1.1 Mha of native forest, about 93% of the extent before colonization. Of this forest, 51% is protected in formal or informal parks and reserves and 14% is on private land. About 19% of forest area is available for timber production. A total of 17,300 ha was logged in the 10 yr to 2017. Since the 1960s, the seed tree harvesting regeneration system has been used on better-quality sites to consistently regenerate these forests after harvesting. About 5–15 trees ha^{-1} are retained, logging slash is burnt in the autumn and seed trees are retained indefinitely[55]. About a third of the area harvested through the 2000s was thinning of regrowth forests[56].

Southern NSW. The total forest area in this region is 3.36 Mha, with 690,000 ha (21%) currently classed as native production forests (NSW Department of Primary Industries 2018). Selective harvesting in production forests increased rapidly after World War II. These forests were logged to economic limits creating mixed age class, multispecies native forests. Clearfelling, originally developed to regenerate wet sclerophyll *Eucalyptus* species forests in Victoria and Tasmania, became more widely practiced in coastal forests in the late 1960s in the Eden area to supply woodchip export markets. More recently, harvesting has been purposefully selective, creating smaller patches of harvested area that naturally regenerate. From 2009 to 2016, a mean of 3,515 ha has been harvested each year.

Northern NSW. Of the 5.7 Mha of native forests in this region within about 150 km of the coast (those covered by Regional Forest Agreements), 47% are privately owned, 33.4% are public forests in conservation reserves and 15.7% are production native forests[57]. Close to the coast are species-rich wet forests that have been systematically selectively harvested since the 1950s. Many species can regenerate in smaller gaps and the system results in uneven-aged stands, with well-formed trees conserved to maintain future sawlog supply[55]. In certain management zones, logging occurs in larger patches to increase the regeneration of commercially desirable species[57].

Plantations. Our analysis is restricted to NSW because of the unavailability of suitable data for plantation areas burnt in eastern Victoria.

Plantations in NSW (0.393 Mha) are predominately non-native conifer (78%), mostly *P. radiata*, with smaller areas of *Eucalyptus* and other hardwood species (22%). Plantations are managed using even-aged systems on the basis of complete harvest and replanting with a rotation of ~28–35 yr. There has been little new investment in plantations since 2010 and some hardwood plantations established on farmland are being harvested and converted back to agriculture. Over half (~65%) the plantations in NSW are managed by the state government business enterprise, Forestry Corporation.

Geographical data. Geographic data for fire extent, severity, harvest date, vegetation type, terrain and time since last fire were assembled for each of the three study areas, using data sources detailed in the Data availability.

Plantations. We intersected the NSW forestry plantation, split into softwood (conifer) and hardwood (*Eucalyptus)* and native production forest estates (derived from 2017 NSW DPIE Landuse mapping) with the statewide fire severity map and extracted statistics of mean-severity pixel values for all fire-severity cells. A frequency distribution table was used to examine the distribution of mean-severity classes across forestry polygons and determine the mode fire severity, with the high- and extreme-fire-severity classes combined into a single class to represent canopy scorch or consumption ('severe canopy damage').

Fire severity. The fire severity mapping sourced from NSW and Victorian government data (Data availability) was generated from methods and severity class definitions that align[38,39]. The method uses the random forest machine-learning algorithm trained on a suite of satellite-derived fire-severity indices. Training samples are derived from high-resolution aerial photograph interpretation of fire-severity classes of previous fires. Fire-severity indices include the relativized differenced normalized burn ratio (RdNBR) as well as multiple other indices that differ between NSW and Victorian methods but achieve consistent accuracy metrics. The fire-severity classes are defined as unburnt, low (burnt understory/unburnt canopy), moderate (partial canopy scorch), high (full canopy scorch) and extreme (full canopy consumption). For the analyses in this study, the response variable, an ordinal scale of four fire-severity classes derived from the satellite image classification, was coded as a binary, with values of 0 representing understory fire (low-fire-severity category) and values of 1 indicating 'severe canopy-damage fire' (combining the high- and extreme-fire-severity categories). The intermediate 'mixed' canopy impact class was excluded due to the potential for classification confusion.

Sample plots, at a density of <1 point per hectare, were randomly generated across the three fire grounds and all variables were sampled at those point locations. After removing points on the basis of excluded vegetation types and severity classes, sample point density in eastern Victoria was 0.81 ha^{-1} ($n = 1{,}061{,}620$), southern NSW was 0.52 ha^{-1} ($n = 481{,}169$) and northern NSW was 0.36 ha^{-1} ($n = 43{,}143$).

Predictor variables. A forest history variable was created, with four classes, indicating if, within the last 25 yr, the point had been burnt, harvested, burnt and harvested or was undisturbed. We used a 25-yr threshold to capture regrowth forests vulnerable to severe canopy damage on the basis of prior research[24,37]. Vegetation type was limited to wet sclerophyll (tall forest) and dry sclerophyll vegetation classes. Points were attributed with the TPI calculated over a 1-km window using the tpi function in the spatialEco package in R (ref. [58]), using an underlying 30-m DEM from the NASA SRTM dataset[59] with positive values of TPI indicating a ridge, negative values indicating a valley and values around zero indicate a relatively flat landscape. FFDI was attributed to each point by combining fire progression isochrons with gridded daily FFDI data[60], with each point taking the FFDI at that location from the date in the middle of the two bordering isochrons.

Statistical models. Statistical analysis was carried out in R v.4.0.0. A set of candidate binomial generalized linear models was constructed (Supplementary Table 1), with the global model including the forest history class, along with fire weather (FFDI), topographic position and vegetation type. For each model, residuals were extracted and generalized additive models (GAMs) were used to generate a two-dimensional spline smooth of residuals ($k = 30$) using the mgcv package. Model predictions from these GAMs were then included in the GLMs as an additional covariate to help control for spatial autocorrelation, using restricted spatial regression[61]. The spatial variable therefore represents residual spatial autocorrelation, at a broad spatial scale, that is not explained by the other predictors. Models were ranked on the basis of AIC using the AICcmodavg package to identify the best model and variable importance was calculated using the varImp function of the caret package, on the basis of the absolute value of the *t*-statistic.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Satellite-based fire severity mapping based on Sentinel-2 satellite imagery[38] was obtained for the Victorian fires from the Victorian Department of Environment, Land, Water and Planning and is available on the Victoria government spatial data portal (https://discover.data.vic.gov.au/dataset/fire-severity-map-of-the-major-fires-in-gippsland-and-north-east-victoria-in-2019-20-version-1-). Severity classes were calculated for the NSW fires using the fire extent and severity algorithm (FESM) developed by Gibson et al.[39] and are available on the NSW SEED data portal (https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm). Forest harvest date for Victoria was obtained from the Victorian Department of Environment, Land, Water and Planning and is available on the Victoria government spatial data portal (https://discover.data.vic.gov.au/dataset/logging-history-overlay-of-most-recent-harvesting-activities). Forest harvest date for NSW was obtained from NSW Forestry Corp on request, with data for older age classes within NSW supplemented with statewide land cover and trees study (SLATS) data provided by NSW Department of Planning, Industry and Environment. The 2017 NSW Landuse mapping was obtained from the NSW seed data portal (https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017-v1p2-f0ed). Fire history and fire progression isochrons were obtained from the Victorian Department of Environment, Land, Water and Planning (https://discover.data.vic.gov.au/dataset/fire-history-overlay-of-most-recent-fires) and were provided by the NSW Rural Fire Service for NSW. Gridded FFDI data are available from the Bureau of Meteorology[60]. TPI was calculated from the NASA Shuttle Radar Topography Mission 90-m digital elevation model with a window of 250 m (ref. [62]). Vegetation type was derived from the National Vegetation Inventory System 4.1 (https://data.gov.au/data/dataset/57c8ee5c-43e5-4e9c-9e41-fd5012536374) for Victoria and from the state vegetation formation dataset for NSW (https://www.environment.nsw.gov.au/research/Visclassification.htm).

Code availability

Code for the analyses is available on FigShare at the following URL: https://figshare.com/articles/software/Drivers_of_the_Severity_and_Extent_of_2019_20_Australian_Fires_and_Forest_Management_-_Data_and_Code/14331530.

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Author contributions
D.M.J.S.B. conceptualized and directed the the study and led the writing. G.J.W. undertook the analyses, produced the visualization and contributed to the writing. R.K.G. prepared data and contributed to the analysis and writing. R.A.B. and R.J.K. contributed to the writing and analysis.

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The authors declare no competing interests.

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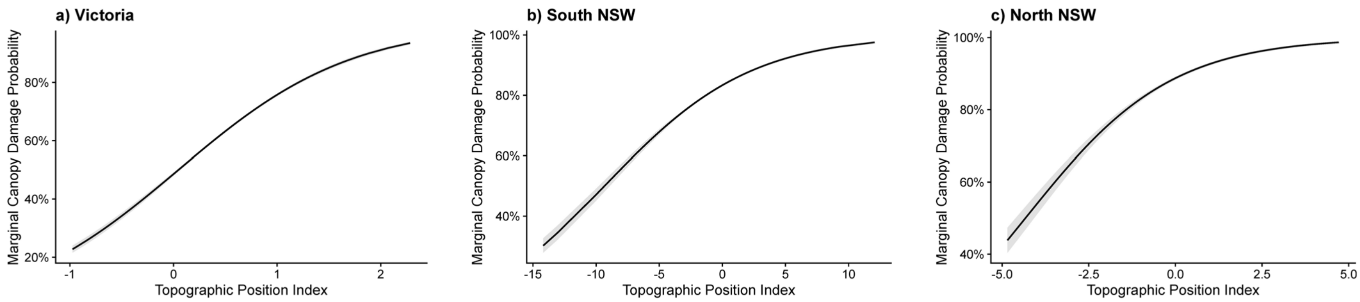

Extended Data Fig. 1 | Marginal effect of topographic position index (TPI) in fire severity for the three study regions. Marginal effect of topographic position index (TPI) in fire severity for the three study regions.

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Study description	A spatially-explicit analysis of satellite-derived fire severity was conducted across three major fires in eastern Australia, determining the effect and relative importance of a range of potential drivers of fire severity, including forestry and fire history, terrain and fire weather.
Research sample	Random points in three fire domains; eastern Victoria (1.3 Mha), southern New South Wales (923,000 ha) and northern New South Wales (119,000 ha).
Sampling strategy	Samples were randomly placed at a density less than 1ha, a sampling density determined by interrogation of semi-variograms.
Data collection	Data is based on available satellite and geographic datasets.
Timing and spatial scale	Data collection spans 2019-2020, across the three regions stated above.
Data exclusions	Fire severity of an intermediate or "mixed" class was excluded because this is often a confused class, and we wanted to restrict the analysis to a binary distinction between canopy damage or no canopy damage.
Reproducibility	Reproducible code and data is supplied.
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