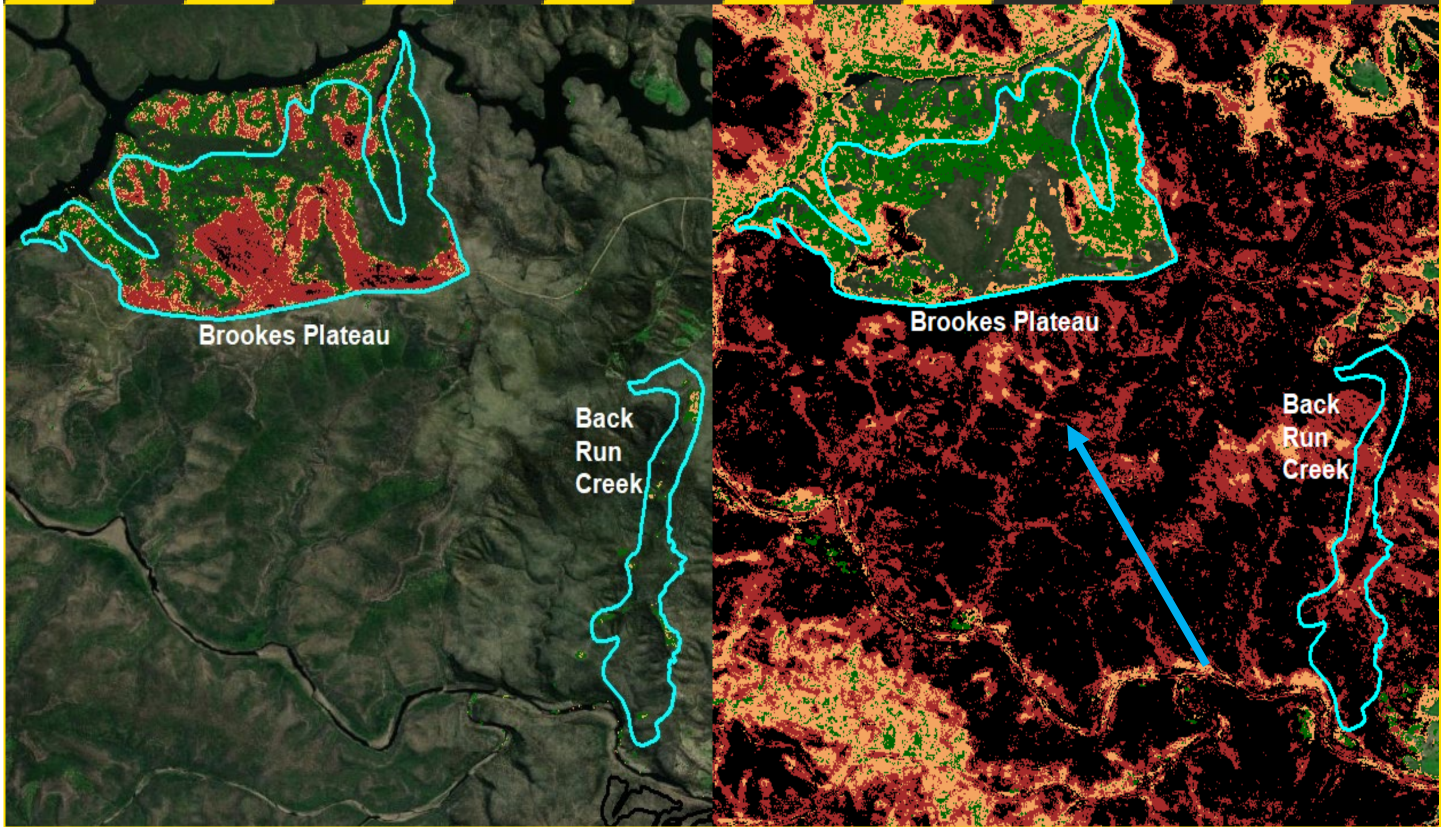
ANALYSIS AND CHARACTERISATION OF BUSHFIRE-MEETS-PRESCRIBED BURN EVENTS FROM THE 2019-20 FIRE SEASON

Owen Price[1,3], James Barker[1], Simin Rahmani[1], Carrie Wilkinson[1,3] & Donald MacDonald[2]
[1]University of Wollongong, [2]National Parks and Wildlife Service &
[3]Bushfire and Natural Hazards CRC



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Cover: Two burns implemented in Moreton National Park, NSW in February/March 2019. The left map shows the Fire Extent and Severity Map for the prescribed burns and the right map shows the Fire Extent and Severity Map in the Currowan bushfire in January 2020. It seems that the severity of the prescribed burn influenced the severity of the subsequent bushfire.

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ACKNOWLEDGMENTS

We would like to thank our colleagues in the NSW Department of Planning, Industry and Environment and NSW Rural Fire Service who helped to develop this project proposal.

This research was part of the Bushfire and Natural Hazards Cooperative Research Centre’s Black Summer research program, funded by the Australian Government and the CRC to investigate key issues from the 2019-20 bushfire season.

EXECUTIVE SUMMARY

The objective of this project was stated in the Research Services Agreement as: "to develop a novel dataset that will capture information about individual bushfire-meets-prescribed burn events. The initial focus will be on those interactions that occurred during the 2019/20 fire season." In other words, the project was to design a database that will allow evaluation of prescribed burns from planning stages to ultimate outcomes, and start using the data for some cases. In this report, we begin by outlining this dataset and its sources of information, though we have not populated it. Instead, we list potential evaluations that could be done with and conduct two evaluations with components of the data.

The core of the proposed fire-meets-fire dataset is matched reporting from the Burn Plan (before) and Burn Report (on completion), especially area, fuel, moisture and weather variables. Some of this is not routinely reported in the current Elements System (for example 21% of burns had no actual area burnt recorded and most burns were missing fuel information). The dataset should also ingest information from fire severity mapping (which is now routine) and smoke impact. If the burn meets a bushfire a new range of information is available and should be ingested, including the severity of the bushfire within the burn. The advantage that the burn gave to firefighters is hard to gauge simply from fire severity, so additional information is needed, most importantly from firefighter interviews, but also by more detailed GIS examination of bushfire behavior.

There are many evaluations that could be done with this dataset, from simple metrics such as percent of planned area actually burnt, to refinement of weather prescriptions for burns to whole-of-program evaluations applied to all burns such as the severity analysis presented here.

Sections 3 and 4 are examples of whole of program evaluations. Section 4 is an analysis of severity reduction in the 2019/20 bushfires relating the occurrence of high severity fire in ~100,000 points to the fire history at those points, and controlling for vegetation, weather and topography. This found that in dry sclerophyll, recent burning (up to ~five years) reduced the probability of high severity fire and even more so if that previous burn was at low severity.

Section 4 uses visual interpretation of the 2019/20 bushfire severity and progression mapping to attribute each previous prescribed burn with its effect on the bushfire. This ranged from stopping the bushfire altogether (having a common boundary) to simple severity reduction (was the bushfire severity reduced in the burn?). We found that 30% of burns from 2014 were encountered by the bushfires. Of these 509 burns, 13% of them were aligned with the final fire boundary, 42% of recent burns (one or two years old) caused some unburnt patches within the burn, and 68% caused a severity reduction. Burns older than this had much less effect, and we found two cases where a burn left an unburnt shadow behind it (meaning shadows are very rare events). We were able to cross-reference our interpretation for 14 burns to interviews from another pilot project. This revealed broad agreement, but also highlighted several cases where a burn gave firefighters an advantage that could not be found in the GIS. Three of these were cases where the bushfire slowed down (sometimes for

several days), allowing firefighters time to prepare. There were two cases where burns outside of the burn perimeter effectively reduced spotting activity.

The project demonstrates what can be done to evaluate prescribed burning programs and that a wide range of data is required to do this thoroughly. The 2019/20 bushfire season was extraordinary in many ways. Our analysis suggests that one of these ways was that prescribed burns only reduced fire behavior if they were one or two years old. Analyses of previous seasons generally find a longer lasting effect. Even so, there were many instances where prescribed burns helped firefighters, including in ways that are not obvious in GIS analyses.

END-USER STATEMENT

Donald MacDonald, *Bush Fire Risk and Evaluation Unit, Fire and Incident Management Branch, National Parks and Wildlife Service, Department of Planning, Industry and Environment, NSW*

Land managers like NSW National Parks and Wildlife Service undertake hazard reduction burning operations across their estate to modify the behaviour of wildfires so that fire agencies can be more readily control wildfires before they impact vulnerable assets. During the 2019/20 fire season, at least 414 prescribed burns conducted by NPWS in the prior five years had some level of interaction with bushfires. However, NPWS, like many land management agencies, did not have an adequate system to rigorously evaluate the effect of these burns on wildfire behaviour, control operations, and asset protection. This program evaluation gap provided the impetus for this Black Summer rapid research project.

The research undertaken by the University of Wollongong has provided NSW with a multi-method framework for combining qualitative and quantitative analysis of burn meets wildfire events. The work has delivered insights about how existing data can be used for hazard reduction program evaluation framework along with the limitations of that data. The results have also provided NPWS with a set of new analysis techniques that could be systematically deployed to improve its hazard reduction evaluation framework. Overall, the work gives the agency insight into the elements of a comprehensive hazard reduction evaluation framework.

NPWS intends to use the outcomes of this research to inform the design of a new hazard reduction program evaluation framework. From the NSW NPWS perspective, it is intended that this work will provide a foundation for engaging partner agencies in the co-design of hazard reduction program evaluation frameworks.

INTRODUCTION/OBJECTIVES

Prescribed burning is a cornerstone of bushfire risk management in southern Australia, but like all risk strategies, it requires evaluation to i) determine the extent to which risk actually is reduced; ii) to quantify any conflicts in the program (i.e. values that are negatively affected); and iii) to design an optimal mix of risk reduction strategies (i.e. place it in the context of other strategies). Ultimately the question is whether the program is cost-effective. Evaluation of prescribed burns is recommended by the National Guidelines for Prescribed Burning Operations (AFAC 2016) and is required by the NSW Enhanced Bushfire Management Program (EBMP). Such an evaluation requires robust data and a repeatable methodology.

Evaluation should consider a hierarchy of risk reduction measures, from the purely operational (was the burn completed) to the ultimate (what was the dollar value of assets saved from bushfire). The Monitoring, Evaluation and Reporting framework for the EBMP refers to these as Activities, Outputs, and Immediate, Intermediate and End of Program Outcomes (referred to here as the EBMP MER framework, DPIE 2021). This hierarchy reflects the lifetime of a burn and the scale of the overall program and is described in Table 1.1. The program starts with a Risk Management Plan which identifies which areas should be burned in a forward program (typically five-years). Each particular fire proceeds with a Burn Plan whose basic purpose is to describe its location, area to be treated, degree of fuel reduction and timing of the burn. A Burn Report is written after the burn is implemented, and describes what was actually achieved in terms of fuel reduction (a map and percent completeness). The Burn Plan and Burn Report are saved in the Elements database maintained by DPIE, but in separate locations that are not routinely matched together. Beginning in 2021, DPIE has also begun creating a fire severity map (called the Fire Extent and Severity Map, FESM), which is usually produced annually for all burns in the state but can be produced on request for any particular fire. Sometime later, the burn may encounter a bushfire and the influence that the burn may have on this bushfire is the reason the burn was conducted in the first place. Information about the response to the bushfire is stored in the ICON system maintained by the Rural Fire Service (RFS). ICON does not specifically record information about the fire-meets-fire event, though there may be reference to the event in one of a number of free-form reporting sections. At present, there is no system for linking the outcome of these events with attributes of the burn, and the main purpose of this report is to address this gap.

Fire-meets-fire events have been the subject of research studies in Australian forests, most commonly into the relationship between prescribed burning and remotely sensed bushfire severity via the effect of time-since-fire. There have been several studies of fire severity in NSW bushfires (Bradstock *et al.* 2010; Storey *et al.* 2016; Barker and Price 2018), including from the 2019/20 fire season (Hislop *et al.* 2020; Collins *et al.* 2021), and similar ones in Victoria (Price and Bradstock 2012; Collins *et al.* 2014; Tolhurst and McCarthy 2016). These universally find that recent burning reduces the severity (and hence also the intensity) of bushfires, but they differ in their estimates of how much reduction occurs and how many years post-burn it lasts (from 3 to 7 years).

There has also been research into the effects of prior burning on the annual area of bushfires (Price and Bradstock 2011), and the spread of bushfires (Price and Bradstock 2010; Price *et al.* 2015). The only study to examine individual prescribed burns was Price and Bradstock (2010), who found that 18% of prescribed burns stopped a subsequent bushfire if encountered within 5 years.

This report will assist in the transition of prescribed burning evaluation into a more formal process that occurs as part of DPIE business. The first section is the design of a database with a record for each burn which can be used for several layers of evaluation. The database draws information from several current data systems, most notably various components of the DPIE Elements data storage system. The second section covers the creation of one component of the database: a set of measures capturing the influence of each burn on subsequent bushfire behaviour that can be observed from GIS mapping. It also includes a simple evaluation of that data. The third section is a quantitative state-wide analysis of the effects of burns on the severity of the 2019/20 bushfires.

The objective of the project as stated in the contract was: “to develop a novel dataset that will capture information about individual bushfire-meets-prescribed burn events. The initial focus will be on those interactions that occurred during the 2019/20 fire season. However, the database could be expanded to include historical fire seasons and be setup to capture information into the future. The database will support multi-criteria statistical analysis of bushfire-meets-burns events. That analysis is intended to provide insights into to the circumstances where prescribed burns are likely to inhibit the spread, reducing severity, or support wildfire suppression strategies and when they probably will not.

Step	Description	Data repository
Burn conceived	Burns begin as part of a regional 5 year plan for a NPWS region or an RFS Bushfire Risk Management Plan	?Held by regional offices, fire boundaries in ELEMENTS?
Burn planned	A detailed Burn Plan is written describing each intended burn (map, fuel reduction objectives, suggested timing).	ELEMENTS
Burn conducted	A brief Burn Report is written describing what was actually achieved in the burn (e.g. burn map, level of fuel reduction). The burn will be added to the DPIE fire history GIS layer. The exact process is not known to the authors. A severity map may be produced in the months after the fire. This should be routine from 2021 onwards.	ELEMENTS DPIE corporate GIS DPIE corporate GIS
Burn meets fire	What happened when the burn is encountered by a bushfire. There is currently no documentation, and this is the subject of this report A severity map for the whole state will be produced in the months after the fire.	DPIE corporate GIS

TABLE 1.1. STEPS IN THE LIFETIME OF A PRESCRIBED BURN. THE DATA REPOSITORY REFERS TO WHERE THIS INFORMATION RESIDES.

1. REQUIREMENTS FOR A FIRE-MEETS-FIRE DATABASE FOR EVALUATION OF PRESCRIBED BURNING

In order to evaluate individual burns and the burn program, data from the planning, implementation and fire-meets-fire event need to be brought together. This section describes a minimum dataset for this purpose and where the information is sourced from.

ABOUT DATA SOURCES

Information relevant to prescribed burning evaluation is stored in a variety of formats in a variety of databases. The most useful sources are listed in Table 2.1. These are mostly corporate databases maintained by DPIE or the Rural Fire Service. There are several issues with the current systems that hinder comprehensive evaluation:

- The databases are complex, and at present, the authors do not have a complete understanding of what is in each database or how they integrate together. As one example, it is possible that an advantage gained by a prescribed burn may be mentioned in ICON, but it is not clear where this is documented among the Situation Reports, Incident Action Plans, a Map Lists, Attached Documents and Event Logs, which for a major bushfire may be more than 1000 separate documents. Thus, using the current databases to evaluate prescribed burning is a classic needle-in-a-hay-stack problem.
- There is no common naming convention for fires across systems. Burns conducted by DPIE will be stored in Elements and will have a unique Brims Number and Elements ID, either of which can be used to match within DPIE systems, but when the burn is transferred to the RFS ICON system, an ICON name is added which is used for all other purposes. ICON and Elements data can be matched via these IDs but it is not necessarily straightforward.
- Fuel Hazard observations are made before and after a burn. These are usually recorded in Elements for both the Burn Plan and the Burn Report, and may also be summarised in the Burn Report (a manual interpretation of several OFH observations). There is also a spatial database of these OFH observations for the whole estate (OCA, see below), but these are not tagged to the burn in which they were taken. It would be possible to identify the burn through a GIS matching process.
- Dead fuel moisture is a key driver of fire behaviour and is routinely used by fire managers to make decisions about when to conduct a burn and what ignition pattern to use. The Burn Plan contains a prescription for the preferred moisture level, but the Burn Report does not record measurements on the day, even though they may have been made. Fuel moisture measurements are usually taken before and after the burn, but they are often not recorded in the reports. Rather they may be in an operations log, either as a digital or hand-written note. Improvement could be made here to ensure they are accessible for evaluation,

perhaps by entering them into a similar database as the OCA fuel hazard database (see under 'data from other intelligence' below.

- A similar problem exists for weather information. Often, weather during the burn is recorded, but on paper or on documents not linked to the Burn Report. This could be improved.
- The main objective of a burn is usually fuel reduction. The Burn Plan has a field for fuel loads in tonnes per hectare, but it is often not filled in. It is more common to record Overall Fuel Hazard (OFH), but it is not clear how this assessment was done. The OFH method (Hines *et al.* 2010) is a composite measure combining surface, near surface, elevated and bark hazard, but these are not recorded. Many separate measures may have been done in the field, but only one is recorded in the plan. The Burn Report sometimes reports the actual OFH measurements from before the fire (information missing in the Burn Plan), and sometimes from after the burn, but often not. There is also a database of OFH measures (called OCA) which may be used to match measurements to each burn. At present, the authors have not investigated how comprehensive the database is, or how feasible it is to match to the Burn Plans and Burn Reports.

The fire-meets-fire database outlined in Table 2.2 aims to extract relevant information from those data sources. Some of the information can be extracted directly from the existing databases into a table field, while some require further analysis or are more complex data structures held outside the database.

Data source	Description
Elements	DPIEs operational data platform. Contains burn plans and burn reports. Available online to registered users.
ICON/Brims/Guardian	RFS operational data platform. Icon Contains incident management information for bushfires and prescribed burns entered as they occur. Brims contains planning information for RFS prescribed burns (those not conducted by DPIE). Guardian is taking over both roles. Available online to registered users.
FESM	DPIEs Fire Extent and Severity Mapping. 10 m resolution severity mapping for all fires from 2019 onwards, and maps for historical fires is underway. Bushfire data available from the public SEED download portal (https://www.seed.nsw.gov.au/), burn data from corporate storage.
OCA (OFH)	A collection of Overall Fuel Hazard measurements (>5000 records), some from prescribed burns. It is maintained by the Fire Incident Management Branch in DPIE
SAP	This is a database of resource and personnel deployments. The authors are not familiar with it at present
BIA	RFS post fire Building Impact Assessment. Identifies which buildings are destroyed, damaged or untouched in destructive bushfires. Available on request.
RFS Smoke predictions	RFS will run their TAPM/CCAM smoke dispersal model for individual prescribed burns on request. The predictions are available as images or grids from online storage (Available online to registered users).
Air Quality Network	DPIE operates ~45 air quality monitors around NSW recording hourly concentrations of various pollutants. Data can be accessed via their website https://www.dpie.nsw.gov.au/air-quality/air-quality-data-services).
Weather	The Bureau of Meteorology (BOM) maintains the weather station network, and make raw data and modelled grids available via a variety of methods. DPIE has dedicated access.

Lessons Learned	DPIE provides a Lessons Learned review process in which staff can fill in a form to explain an event. Some of these may relate to burns or fire-meets-fire events.
Interviews	DPIE developed and trialed a process for interviewing firefighters about their experience at fire-meets-fire events in 2020 (the Lessons Learned process). This process is running in parallel with this report, but it is intended that the interviews will be coded into information that can be directly used in this database. This will classify the operational advantage gained by the burn when the bushfire met it. There will be a limited number of interviews.

TABLE 2.1. USEFUL DATA SOURCES FOR THE DATABASE.

Variable	Source	Notes
From Burn Plan		
Burn Name/Number	Various	There needs to be a key burn identifier across all systems (Elements, Brims, ICON etc.). We are advised that there is a Hazard Number common to all systems, but we have only seen it in the Burn Reports
Planned Area	Elements	
Time Since Last Fire	Elements	
Vegetation Type	Elements	Text
Assets to be Protected	Elements	Text
Fuel Load	Elements	This is rarely filled in
Overall Fuel Hazard	Elements	actual OFH observations before the burn are listed below from Burn Report
Optimum FFDI	Elements	Text
Preferred DF	Elements	Text range
Preferred Fuel Moisture	Elements	Text range
Preferred Temperature	Elements	Text range
Preferred Wind Speed	Elements	Text range
Preferred Wind direction	Elements	Text
Preferred RH	Elements	Text range
Aim and Objective	Elements	Text Extract % of area to be treated
Desired OFH	Elements	RFS records t/ha using table conversions
From Burn Report		
Actual Area Burnt	Elements	
Pre-fire OFH	Elements	
Pre-fire OFH count	Elements	Number of OFH measurements taken
Post-burn OFH	Elements	NB this is rarely present
Post-burn OFH count	Elements	
Start Burn Day	Elements	
End Burn Day	Elements	Usually day fire is declared at “Out” status
Fuel Moisture		This is not currently recorded but ought to be in order to match the Burn Plan and also because it is useful for developing predictive tools. See note above.
From other intelligence		
Calculated Change in OFH	Calculation	This is just the difference in pre and post OFH
Patrol day from ICON	ICON	The day that the fire was declared at “Patrol Status”
OFH from OCA database. Pre and post	OFH	The OCA database contains multiple OFH records from before and after the burn. An algorithm is required to match these to the fire and calculate the change.
Time Since fire from GIS		
FESM % unburnt	FSEM	% of the planned area
FESM % low severity	FSEM	As above
FESM % moderate severity	FSEM	As above
FESM % high severity	FSEM	As above
Resources used	SAP AMS	Broken down by type (personnel, tankers, aircraft).From SAP or ICON. Still discussing this
Smoke prediction	RFS	To be further explored, however, RFS predictions can be summarised in various ways
Smoke impact	OEH Air quality data	24hr average PM$_{2.5.}$ from nearest NSW AQ station and mean of all Sydney stations.
Actual HR weather	BIOM	From BOM data

From Fire Meets Fire event		
Bushfire Name	ICON	
Bushfire ICON ID	ICON	
Bushfire Start Date	ICON	
Fire-meets-fire Date	GIS manual	Estimated manually examining GIS (progression etc)
ROS at arrival	GIS manual	As above
Orientation of HR wrt Bushfire	GIS manual	As above
FESM % area unburnt	FSEM	% of the planned area. Calculated using GIS
FESM % low severity	FSEM	As above
FESM % moderate severity	FSEM	As above
FESM % high severity	FSEM	As above
Operational advantage	Interviews	Theme, category and sub-category from interviews. See APR Interviews report (Wilkinson 2021) for more information and examples. May be more than one.
Operational advantage descriptive	Interview	Free-form description of above.
HR Effect GIS	GIS manual	Hierarchical: Leave unburnt shadow/ Stop leading edge/ Stop trailing edge/ Reduce severity/No effect
Number of houses in vicinity	GIS spatial analysis	e.g. within 500m (from Geoscape). Don't worry about direction
Proportion of houses impacted	RFS BIA	As a proportion of above (from BIA)
Lessons Learned text	NPWS LL DB	Text from Narrative or Observation boxes
Attachment list		Filenames, e.g. LineScan, FESM image. This is just a discussion point at present.

TABLE 2.2. LIST OF DATA FIELD FOR THE FIRE-MEETS-FIRE DATABASE.

*Red text: these areas are not finalised and require further discussion

DATA FOR ALL BURNS

Data from the Burn Plan

The burn plan is completed months or sometimes years before the burn occurs and is stored in Elements. It contains over 100 fields of information relating to the location, objectives and operation strategy of a burn, including the area, desired fuel reduction, preferred weather windows, safety, resource requirements and one or more maps (in PDF format). An extract of the quantitative fields stored in the Elements database is provided in Table 2.3. It shows that the format of the entries varies considerably, and a detailed process will be required to convert them to numbers. Many of them are free-form text, which makes standard extraction, for example, the vegetation and list of assets to be protected. We have determined that 16 of them are useful for evaluation. Most important are the area, objective and current Overall Fuel Hazard. These can be compared against the subsequent burn report to evaluate the burn objectives. Note that the most useful part of the objective is usually the percentage fuel reduction to be achieved. This will need to be extracted algorithmically from the free text entry in the objectives field. There are also fields for the desired weather conditions for the burn. These can be compared to the conditions in the subsequent burn plan to test the extent to which preferred burn windows are met and whether they are appropriate.

Data from the Burn Report

Once a fire is completed immediately after a burn is conducted. It contains approximately fields, many of which are copied from the Burn Plan, and it may also include a map (PDF). Of most use is the actual area burnt, dates and post-fire OFH. Pre-fire OFH is often collected, and this may be more useful than those in the burn plan because it is just before the burn is conducted. However, notice that the OFH score has rarely been collected comparing pre and post-fire OFH will be difficult for past burns. Notice also that fuel moisture is not recorded in the Burn Report, even though it is one of the prescribed measures in the Burn Plan and is regarded as an important driver of fire behaviour and burn completeness (Slijepcevic *et al.* 2015).

Data from other intelligence

Much information about the immediate outcome of a particular burn is not available in the Burn Report and must be sourced from elsewhere.

Fire mapping. Time since fire can be extracted from the current fire history, versions of which are maintained by DPIE and RFS. DPIE now routinely maps the severity of fires (the FESM product). The evaluation database should include summary information from the severity mapping (% unburnt, burnt as low, moderate and high severity). It might be useful to also include a hyperlink to the relevant severity map which is stored on an online database available to registered users.

Resources used in the burn. Evaluation of costs and resources required to achieve planned outcomes requires information on what resources were used in the burn. This is available from the RFS Icon or DPIE Sap systems. The degree of detail to include needs to be carefully considered, but it should at least separate personnel, fire trucks and aircraft.

Smoke impact. This includes information about any smoke impact on the community. This is difficult to assess without undertaking a forensic analysis of each fire, but a relatively simple measure is the 24 hour mean particulate concentration ($PM_{2.5}$) from the closest DPIE air quality station. Note that in most cases there will be no detectable impact because the closest station is too far away. Many prescribed burns were also subjected to a smoke prediction model run by RFS. These are stored on an on online repository for registered users. A hyperlink to that prediction could be included in this database.

OFH database (OCA). DPIE maintains a database of OFH observations which are sourced from a variety of surveys including pre and post prescribed burns. As of 2017 there were more than 5000 observations in this database. This data can be interrogated retrospectively to improve the OFH data recorded in the Burn Plans and Burn Reports.

Appropriate end date. The Burn Report includes the date that the fire was declared out, but this is not a useful date for many evaluation purposes. Usually, a fire becomes functionally inactive many days before being declared out. For example it does not spread and does not produce smoke. Fire operations can be grouped into six stages demarking the progression between being out of control and declared out (Simpson *et al.* 2019). For the purpose of evaluation, the fifth stage (Patrol) is the most useful. It defines when the fire is no longer active or growing and resources are reduced to the minimum requires to check for flare-ups. We recommend using the date of the Patrol declaration, which can be sources from the RFS Icon incident data system.

BOM weather data. The actual weather during the burn should be obtained from Bureau of Meteorology data. There are many options for this, with the simplest being sourcing hourly data from the nearest BOM station. Distance-weighted average values or modelled grids are alternatives.

FOR BURNS ENCOUNTERED BY A BUSHFIRE

Information about the bushfire comes from a variety of sources.

From GIS analysis

Event metrics. A GIS intersection between bushfire and burn can be used to find the name, ICON Id and start date of the bushfire.

Fire severity. The FESM severity map should be available within a few months of any bushfire. The same measures as produced for the original burn should be calculated for the subsequent bushfire (that part within the burn perimeter): percent unburnt, low, moderate and high severity.

Manual GIS process. With the exception of burn severity, the influence of the burn on the bushfire can be hard to determine automatically. Instead, a manual process is needed to gather information from various GIS layers. Most important is the use of a progression map to estimate the likely direction and rate of spread of the bushfire at the time they met. With this information, it is possible to estimate visually the orientation of the burn with respect to the bushfire (0 degrees is at right angles, 90 degrees is in-line), and whether the burn caused the bushfire to reduce in severity, stop or leave an unburnt shadow in the wake of the burn. This is the subject of section 4.

Interviews. Often, the operational benefit of a burn cannot be measured from a GIS because its effects relate to the deployment of resources or the suppression methods applied (information that is not recorded in GIS information). This tactical use of a burn can only be obtained by interviewing firefighters or incident controllers with first-hand knowledge of the operation. There is a current DPIE project using interviews to assign the role of the burn into a hierarchical 'scaffold' comprising themes, categories and sub-categories. The project is being conducted as an internship by a current PhD student. We refer to this project as the APR Interviews, and have used it to cross-reference the GIS analyses in Section 4. There is also a report (Wilkinson 2021). There are five themes describing the way the burn may have helped: Containment Strategy, Resource Productivity and Effectiveness, Firefighter Safety, Aviation, Decision Making. Examples of categories include assisting backburning (Containment theme), reduced mop-up (Resource Productivity theme) or improved visibility (Firefighter Safety theme). It is not expected that interviews will be conducted for every burn, so this information will be available for a subset of them. The choice of interview is important because there is potential to bias evaluation of burns, for example if interviews are only conducted on successful ones or conversely on ones that gave no operational advantage.

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Fire Name	Proposed Burn Area (ha)	Time Since Fire	Pre-Burn Overall Fuel Hazard	Optimum FFDI	Drought Factor	Fuel Moisture	Temperature (C)	Wind Speed (km/h)	Wind Direction	Relative Humidity (%)	Desired Post-Burn OFH
Arakoola South East	617.21	10	Moderate	5-12	5-10	9-16	<27	<15	West	20-40	Low
Awaba Bay South HR	11.42		Very High	9-12	6-9	9-16%	15-28	<15	SW or W	35-65%	Moderate
Banana Hill HR	183.5	7	Very High		6	>10% and <20%	15-25	<15	SE	>30% and <50%	Moderate
Beachview HR	29.5	13	Very High	3-10	7-9	10-22% - (10-14% ridges, 14-16% midslope, 12-22% gully)	15 - 25	10 - 15 (at 10m) & 0-24 (at ground level)	N - NW	35 - 65	Low
Bear Gap	3777.3	2003	High	Mar-14	2-6	11-13	15-25	<25	Any	30-75	Low
Belah Trail HR	68.8	43	Low	3 (Medium) - 22 (High)	7-10	8-12	20-30	3-15 (as measured by Kestrel at 1.5 metres)	Easterly	15-45	Low
Belford East 1 HR	14.59	75	Moderate	5 (Low) - 11 (Moderate)	<8	15-35	15-26	0 -15	north west, west, south west	30-50	Low
Bermaguee HR	153	12	Very High	6-10	7-10	~ 13%	25-12	up to 25 km/h	NE	between 40 and 60%	Moderate
Big Tolbar 1	2259.3										
Black Jack Mountain	5597.6	2003	Very High	Mar-14	2-Jun	11-13%	15-25	<15	Any	30-75	Low
Blue Creek	1452.7	15	High	4-10 (low to moderate)	6-10	12-14	15-25	<15	Preferred wind north through east to south to reduce smoke impact upon Yarrangobilly Caves. Could be any other direction if light.	>30	Low

TABLE 2.3. AN EXAMPLE EXTRACT FROM THE BURN PLAN AS STORED IN ELEMENTS. THIS DOES NOT INCLUDE THE SEVERAL LONG FREE-TEXT FIELDS SUCH AS OBJECTIVES, ASSETS AND VEGETATION TYPES.

2. OPTIONS FOR EVALUATION

There are many useful evaluations of prescribed burn that could be done, some of which can form part of the formal program evaluation and some are more fundamental research. Some suggested ones are listed in Table 3.1. In most of these, the evaluation itself is a simple metric, but there are also possibilities to explore the reasons for the results. For example when comparing the planned and actual area burnt, once a reasonable sample of cases is reported, then an analysis could explore the role of weather, fuel moisture or ignition pattern on mis-matches. The same applies to most of the metrics. The evaluation may address the MER framework for the EBMP, though at present that framework does not give details of the actual analyse that should be done.

Metric evaluated	Description/purpose
Area burnt	Compare objective to actual.
Fuel load reduction	Compare objective to actual fuel load or OFH
Burn Objectives met?	Yes, no, overachieved. Why? This relates to text-based objectives.
Burn Windows	What are they in practice? How did the actual compare to the prescription, how did they affect burn outcomes, including burn completeness and escapes?
Resources used	This can be used to analyse how resources affected burn outcome and cost-effectiveness in bushfire events
Smoke impact	Did the burn cause an Air Quality event? How did it compare to the prediction?
Bushfire behaviour change	How did the burn affect subsequent bushfire behaviour? This is explored in detail in Section 4 of this report.
Firefighting advantage	How did the burn affect firefighter effectiveness in subsequent bushfires? This is the subject of the APR interview project (Wilkinson 2021).
Program effectiveness	Various metrics based on multiple burns to evaluate the overall burn program. Examples are the analysis of severity against burn age as in Section 4 of this report, or leverage analysis as in previous research (Price and Bradstock 2011; Price et al 2015).

TABLE 3.1. SUGGESTED METRICS FOR EVALUATING PRESCRIBED BURNS.

To explore how suited the current data is for evaluation, we requested an extract from Elements and were provided with data for 629 burns from 2015 to 2021 (for the whole state). The extract matched burns from the Burn Plans and Burn Reports to provide information on the actual area burnt and post-fire fuel hazard. 21% of the burns had zero area recorded in the Burn Reports. 38% of pre-fire and 32% of post-fire OFH fuel hazard scores were not recorded, and only 43% recorded both. Excluding the burns with zero recorded area, most burns achieved at least 77% of the planned area, 71% of burns achieved 100% and 2% (13 burns) burnt at least 25% more than was planned (Figure 3.1).

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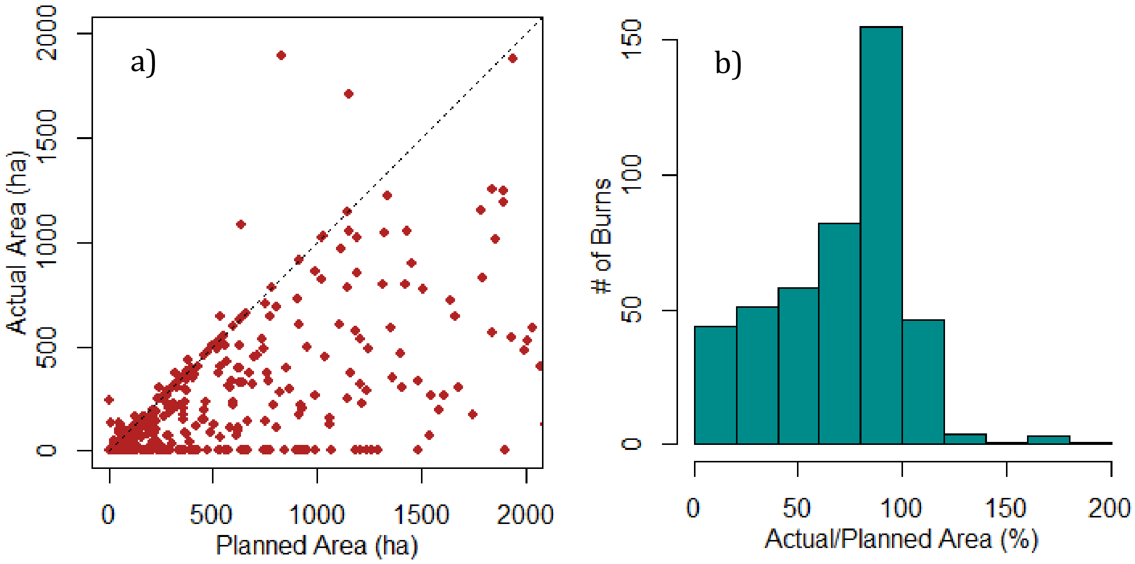

FIGURE 3.1. PLANNED AND ACTUAL AREA BURNT FROM BURNS EXTRACTED FROM THE BURN PLAN AND BURN REPORTS IN ELEMENTS: A) SCATTERPLOT OF PLANNED AND ACTUAL AREA; B) HISTOGRAM OF PERCENTAGE COMPLETED (EXCLUDING THOSE WITH ZERO AREA IN THE BURN REPORT).

3. THE SEVERITY OF THE 2019-20 FIRES IN AUSTRALIA WAS INFLUENCED BY PAST FIRES

Note this section is formatted as a scientific paper for peer review publication.

ABSTRACT

The 2019-20 fire season impacted an unprecedented extent in south-east Australia and reburned many areas which burnt less than one to more than fifty years ago. It is established that fire behaviour can be influenced by the patterns of previous fires, so how was the severity of the 2019-20 fires affected by previous fire? We hypothesised that 1) the amount of high severity fire would increase as the time since the last fire increased, 2) the amount of high severity fire would be lower after previous prescribed fire than after previous wildfire, and 3) the amount of high severity fire would be higher after previous high severity fire than after previous low severity fire. To test these hypotheses, we used a grid of points to sample existing datasets in three forest types over the footprint of the fires in New South Wales. A subset of the data was used to examine the effect of previous fire severity. We found that the proportion of high severity fire was lower after previous prescribed fire and increased with time since fire in dry sclerophyll forests but not wet sclerophyll or rainforest. There was less high severity fire after previous low severity fire in wet and dry sclerophyll forest. We found that these relationships vary between fires due to differences that were not captured by the variables used in the models. Although the 2019-20 fire season was largely driven by drought and favourable fire weather, the severity of the fires was still affected by previous fire.

INTRODUCTION

From June 2019 to May 2020 in New South Wales (NSW), Australia, fires burned along the entire length of the state, with a total area of 5.37 million Ha burnt (State of New South Wales and Department of Planning Industry and Environment 2020). The large extent of these fires has been attributed to the low live fuel moisture content throughout the landscape due to severe drought preceding the fire season, and favourable fire weather which drove the spread of the fires (Nolan et al. 2020, Boer et al. 2020, Bradstock et al. 2020, Deb et al. 2020, Bowman et al. 2021). The fires resulted in 2,475 house losses and 25 human fatalities in NSW (Filkov et al. 2020) and impacted the ranges of a large number of plant and animal species, including a high proportion of threatened species (Ward et al. 2020, Gallagher et al. 2021).

The 2019-20 fires burnt with a mix of fire severities and the proportion of high severity fire was not different to previous fire seasons (Collins et al. 2021a). However, due to the scale of the fire season, the total extent of high severity fire was high (Collins et al. 2021a). Fire severity represents the physical impact of fire on vegetation structure; in forests, low fire severity affects only the understory and the taller strata are increasingly scorched or consumed as fire severity increases (Keeley 2009, McCarthy et al. 2017, Gibson et al. 2020). As such, it is an important measure of the effect of fire on ecosystems and fuel structure.

Fire severity can be influenced by previous fires in the landscape, which is often examined through the length of time since the last fire or the number of past fires in an area. Less commonly examined is the previous fire type (e.g., wildfire or prescribed fire) or the severity of previous fires. Fire alters the amount and arrangement of fuels in a system, influencing the behaviour of subsequent fires. Indeed, this is the main goal of prescribed fire in NSW, to reduce fire risk by modifying fuel (Morgan et al. 2020). The effectiveness of prescribed burning at reducing the severity of the 2019-20 fires has been examined by Hislop *et al*. (2020). They used paired plots to compare areas of the 2019-20 fires which reburned recent prescribed fires to areas with no previous fire and found that 48 % of the previously burnt areas had lower fire severity than previously unburnt areas. More recent prescribed burns were found to have a stronger reduction in fire severity, which is also supported by several studies from previous fire seasons (Fernandes and Botelho 2003, Price and Bradstock 2012, Tolhurst and McCarthy 2016).

Fire severity is also influenced by the severity of previous fires. This has been the subject of recent studies in south-east Australia, where high severity fire was found to be more likely after previous high severity fire in resprouting eucalypt forests in the Greater Blue Mountains region of NSW (Barker and Price 2018) and the West Gippsland region of Victoria (Collins et al. 2021b). Barker and Price (2018) suggested that this relationship was due to structural changes to the forest caused by the initial high severity fire, increasing vertical fuel connectivity due to vigorous regrowth in elevated fuels. This was supported by Collins *et al* (2021b), who conducted field sampling of fuel structure in their study area. They found increased vertical connectivity between understory and canopy at high fire severity sites due to epicormic and basal resprouting of trees, while low severity sites had a larger gap between fuel strata. These studies examined only past wildfires and not prescribed fires, which are generally lower in intensity and severity.

The aim of this study was to determine if previous fires reduced or increased the severity of the 2019-20 fires by examining past prescribed fires and wildfires which were reburned in 2019-20. We hypothesised that 1) the amount of high severity fire would increase as the time since the last fire increased, 2) the amount of high severity fire would be lower after previous prescribed fire than after previous wildfire, and 3) the amount of high severity fire would be higher after previous high severity fire than after previous low severity fire.

METHODS

Study area

The 2019-20 fires burnt an area of 5.37 million Ha in New South Wales, primarily on the east coast and ranges (Figure 1). The 2019-20 fire season started in August 2019 in Northern NSW and progressed down the coast until the beginning of March 2020 (Bowman et al. 2020) following a period of severe drought (Nolan et al. 2020, King et al. 2020). There were periods of extreme fire weather, which drove rapid expansion and high intensity in several fires.

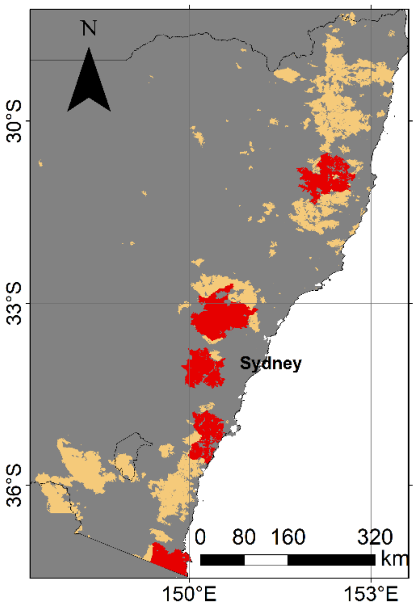

FIGURE 1. EASTERN NEW SOUTH WALES, AUSTRALIA, WITH THE TOTAL EXTENT OF THE 2019/20 WILDFIRES FOR THE STATE SHOWN IN YELLOW. AREAS HIGHLIGHTED IN RED ARE THE INDIVIDUAL CASE STUDY FIRES USED IN THIS STUDY,

Eastern New South Wales has a temperate climate with a gradient of temperature decreasing from north to south, with cooler temperatures in higher elevations along the length of the state. Precipitation is higher in the east, decreasing towards the west (Bureau of Meteorology 2020). The study area is dominated by temperate forests: dry sclerophyll forests, wet sclerophyll forests, and rainforests. Dry and wet sclerophyll forests are dominated by trees in the genera *Eucalyptus*, *Corymbia*, and *Angophora*, which are tolerant to fire (Gill 1981, Collins 2020), and both are characterized by an open canopy structure. Wet and dry forests can be differentiated by canopy height and understory composition. Wet forests have tall trees and mesophyllous understory species, while dry forests have shorter trees and a sclerophyllous understory (Keith 2004). There are pockets of remnant subtropical and temperate rainforest throughout eastern NSW. Rainforests are highly diverse, with a closed canopy and usually lacking any Eucalypt species. They occur in wetter areas with more fertile soils than those of sclerophyll forests and are historically free of fire, so rainforest species are generally less fire tolerant (Keith 2004).

Data

Most of the data used in this study are previously published datasets (Table 1). The severity of the 2019-20 fires was obtained from the NSW State Government's Fire Extent and Severity Mapping (FESMv3), which was derived from Sentinel-2 satellite imagery using random forest methods. This method produces more accurate fire severity maps than previous dNBR and dNDVI techniques, though all three are derived from differences in pre- and post-fire imagery using combinations of spectral bands (Collins et al. 2018, Gibson et al. 2020). Fire severity in 2019-20 is classified into four categories based on scorch height and canopy consumption. For this study we reclassified the two highest categories, high and extreme, as high fire severity, and the two lower categories, low and moderate, as low fire severity. Areas classified as unburnt were excluded. Any previous fires between 2017 and 2019 were also mapped using this method. The severity of the fires before 2017 were derived from Landsat imagery using dNDVI

(Hammill and Bradstock 2006). This mapping only included large wildfires and no prescribed fires; the severity of previous prescribed fires was only available between 2017 and 2019. All fires prior to the 2019-20 fire season were classified ito low, moderate, and high fire severity.

Data	Source
2019-20 fire severity, 2017 – 2019 fire severity	(State Government of NSW and Department of Planning Industry and Environment 2020)
Pre 2017 fire severity	(Hammill and Bradstock 2006, Hammill et al. 2010)
Time since fire, fire frequency, minimum inter-fire interval, fire names, previous fire type	Derived from (Department of Planning Industry and Environment 2020)
Vegetation type	(Keith and Simpson 2010)
Slope, aspect, topographic position, compound topographic index	Derived from (Geoscience Australia 2015)
Live fuel moisture content	(Nolan et al. 2016, Nolan 2020)
Forest Fire Danger Index	(Williamson and Price 2020)
Time since logging	Natural Resources Commission (unpublished data)
Mean annual precipitation and temperature	(Booth et al. 2014)
Road width and proximity	Derived from (Geoscience Australia 2006)

TABLE 1. THE DATA USED FOR THIS STUDY AND THEIR SOURCES.

The time since fire data was derived from fire history mapping (Department of Planning Industry and Environment 2020) with records dating to 1970 for most areas, but with some older records. Areas which were not recorded as burnt in this mapping were given a time since fire of 100 years, but they may range from 50 years to much longer unburnt. Time since fire was then split into six age class categories: 0–2, 3–5, 6–10, 11–30, 31–49, and >50 years (Appendix 1: Figure 8) to analyse the difference between recent and older times since fire. The minimum inter-fire interval and fire frequency were also derived from this mapping, by finding the smallest difference between fire years for each area and counting the number of fires for each area, respectively.

A grid of sampling points, 500 m apart, was created over the study area. This distance has been used in previous studies of fire in NSW and minimises spatial autocorrelation (Bradstock et al. 2010, Storey et al. 2016, Barker and Price 2018). Intersecting values of each fire and environmental dataset shown in Table 1 were extracted to each point. The Forest Fire Danger Index, a measure of fire weather, was assigned to each point based on fire progression data produced for the

NSW Inquiry into the 2019-20 Bushfires (Williamson and Price 2020). Each progression polygon had a distance-weighted value of the maximum FFDI for the period of that polygon based on hourly weather observations from Bureau of Meteorology weather stations and 17 portable monitors deployed during the fire season (Appendix 1: Figure 9a). Road width and the distance of each point to the nearest road were derived from Australian geodata (Geoscience Australia 2006) using the Phoenix RapidFire guidelines (Tolhurst et al. 2008, Fire Prediction Services 2019) to account for fuel discontinuities in the landscape and potential suppression activities, which are generally conducted along roads or trails.

Analysis

The data were split into three forest types for analysis: dry sclerophyll, wet sclerophyll, and rainforest, which were then subsampled to get an equal sample size of each previous fire type per forest type. The data were analysed using binomial mixed-effects generalised linear models using the mgcv v1.8-28 package in r (Wood and Wood 2019) with the response variable for each model being whether each point experienced high fire severity in 2019-20.

Model selection based on AIC (Burnham and Anderson 2002) was used for each forest type with previous fire type and time since fire retained in each model, and previous fire severity retained in each subset model. Potential interactions between variables were included in the model selection process. Each model also included three random effects: the identity of each fire in 2019-20, the mean fire severity of the eight nearest surrounding points, and a 2D smooth term of the coordinates of each point. The identity of the fires was used to account for the different sizes of each fire, and any possible variation between fires that was not explained by the other variables. Mean fire severity was used to account for lack of spatial independence, especially because large fire runs occurred in some places, where the severity of a particular point was likely highly dependent on the severity of nearby areas. The 2D smooth term accounted for any other unexplained spatial patterns. live fuel moisture content was log transformed in the analyses as it had few observations at higher values (Appendix 1: Figure 9b).

Time since fire

The full dataset was used to analyse the effect of time since fire on the amount of high severity fire in 2019-20 for the three forest types. Since time since fire was the targeted predictor, it was retained in each possible model throughout the model selection process.

Previous fire type

The full dataset was also used to analyse the effect of the previous fire type on the amount of high severity fire in 2019-20 for the three forest types. Fire type was analysed separately to time since fire as the unburnt category is correlated to the >50-year age class. Previous fire type was retained during model selection.

Previous fire severity

Previous fire severity data was not available for the entire study area, so a subset of the data for each forest type was sampled where there was previous fire severity data. This was used to analyse the effect of previous fire severity on the amount of high severity fire in 2019-20. This was only analysed in wet and dry sclerophyll forest (Appendix 1: Figure 10) as rainforest had insufficient data. Previous fire severity was retained during model selection.

Case studies

Seven case study fires were also chosen for separate analysis of time since fire because a general model may not have detected variation due to local factors and the distribution of time since fire varied between fires (Appendix 1: Figure 11). The selected fires were: Gospers Mountain, Green Wattle Creek, Carrai Creek, Carrai East, Ruined Castle, Currowan 2, and the Border fire (Figure 1). These fires were spread across the extent of the total fire footprint and were some of the largest fires of the season. They have also been the subject of closer inspection by authorities due to their high impact on assets and the landscape. Not all these case studies had previous fire severity, so it was not included in any of the case study models. Since this analysis was examining individual fires from the season, the fire identity random effect was not used.

RESULTS

Models for time since fire

In dry sclerophyll forests (n = 33000), time since fire had a non-linear relationship to the amount of high severity fire in 2019-20 (Appendix 2: Table 2). Areas which reburned within two years of the previous fire had 30 % high severity fire, while a 3–5-year reburn had ~ 50 % high severity fire (Figure 2). The amount of high severity fire became less after 10 years since the previous fire. For wet sclerophyll forest (n = 27000), times since fire between three and thirty years, and over fifty years, had a significantly higher severity fire than those up to two years but the amount of high severity fire remained between 4 % and 10 % for all age classes. Areas with a time since fire between 31 and 49 years were not significantly different than 0–2 years (Appendix 2: Table 2). In rainforest (n = 1500), the proportion of high severity fire was ~ 5 % in areas between 31 and 49 years since the last fire compared to ~ 10 % in areas up to two years since fire (Figure 2); no other times since fire were significantly different from the 0–2- year category (Appendix 2: Table 2). The amount of high severity fire in 2019-20 was consistently greater in dry sclerophyll forest than in the other two forest types (Figure 2).

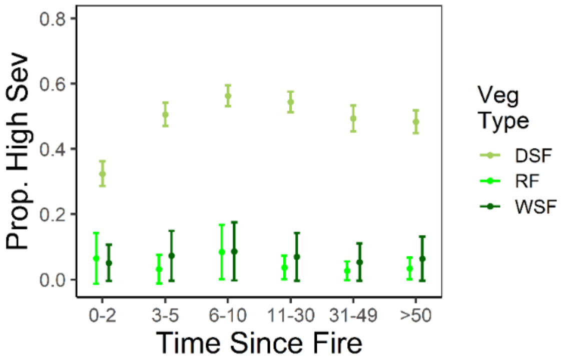

FIGURE 2. MARGINAL EFFECT PLOT OF THE EFFECT OF TIME SINCE FIRE ON THE AMOUNT OF HIGH SEVERITY FIRE IN 2019-20 FOR THREE VEGETATION TYPES: DRY SCLEROPHYLL FOREST, WET SCLEROPHYLL FOREST, AND RAINFOREST. POINTS REPRESENT MEANS AND ERROR BARS ARE 95% CONFIDENCE.

The model for dry sclerophyll forest explained 11.9 % of the deviance, compared to 9.04 % in the null model. The full model included the variables slope, mean annual precipitation (MAP), mean annual temperature (MAT), Forest Fire Danger Index (FFDI), live fuel moisture content (LFMC), and an interaction between MAP and MAT (Appendix 2: Table 2) and there were no other supported models within 2 AIC. The model for wet sclerophyll forest explained 14.5 % of the deviance, while the null model explained 11.4 %. The model included FFDI, time since logging, slope, MAP, LFMC, and compound topographic index (CTI) (Appendix 2: Table 2). There was one other supported model within 2 AIC which included an interaction between FFDI and time since fire, but it did not have a significant effect, so it was not included in the final analysis. The rainforest model explained 35.4 % of the deviance, compared to 29 % in the null model. The variables included in the model were FFDI, aspect, MAP, MAT, and LFMC (Appendix 2: Table 2). There were two other supported models within 2 AIC, but they did not add any extra variables.

Slope had a significant negative effect on the amount of high severity fire in 2019-20 in wet and dry sclerophyll forests (Figure 3a). Mean annual precipitation negatively affected the amount of high severity fire in wet sclerophyll forest but did not have a significant effect in rainforest (Figure 3b), and mean annual temperature had a positive effect on the amount of high severity fire in rainforest (Figure 3c). In dry sclerophyll forest there was an interaction between MAP and MAT. At lower temperatures, the amount of high severity fire decreased slightly with increasing precipitation, but at higher temperatures, there was a positive relationship between MAP and the amount of high severity fire (Figure 3d). The amount of high severity fire was positively related to FFDI in all three forest types (Figure 3e). The amount of high severity fire decreased as time since logging increased in wet sclerophyll forest (Figure 3f). Aspect was included in the model for rainforest but did not have a significant effect on the amount of high severity fire (Figure 3g). There was a negative relationship between live fuel moisture content and the amount of high severity fire in all three forest types (Figure 3h).

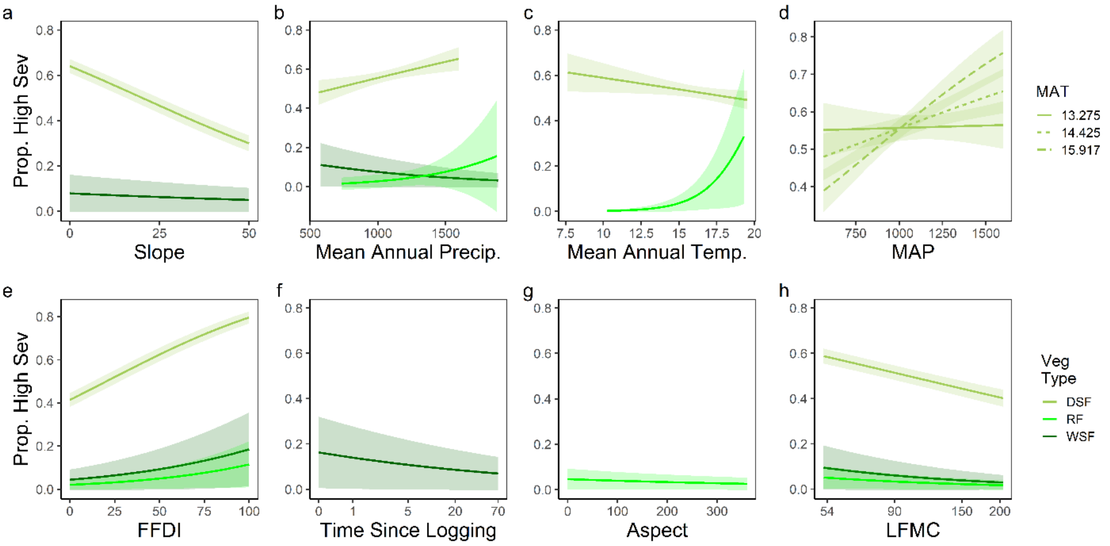

FIGURE 3. THE MARGINAL EFFECTS OF EACH PREDICTOR ON THE AMOUNT OF HIGH SEVERITY FIRE IN 2019-20 FOR THE THREE VEGETATION TYPES: DRY SCLEROPHYLL FOREST, WET SCLEROPHYLL FOREST, AND RAINFOREST. LFMC IS LIVE FUEL MOISTURE CONTENT, FFDI IS THE FOREST FIRE DANGER INDEX, MAP IS MEAN ANNUAL PRECIPITATION, AND MAT IS MEAN ANNUAL TEMPERATURE. THE INTERACTION BETWEEN MAP AND MAT IS IN THE DRY SCLEROPHYLL FOREST MODEL. LFMC AND TIME SINCE LOGGING ARE ON LOG SCALES. SHADED AREAS REPRESENT 95 % CONFIDENCE.

Models for previous fire type

There was more high severity fire in 2019-20 after previous wildfire than after previous prescribed fire or in previously unburnt areas in dry sclerophyll forest (n = 33000), though the proportion of high severity fire was around 50 % for all three categories. In wet sclerophyll forest (n = 27000), there was more high severity fire in previously unburnt areas, or those previously burnt by wildfire, than in areas burnt by prescribed fire but there was never more than 10 % high severity fire. There was no difference in the amount of high severity fire between different previous fire types in rainforest, which remained around 5 % (n = 1500) (Appendix 2: Table 3, Figure 4a). In wet sclerophyll forest there was an interaction between previous fire type and FFDI, whereby the amount of high severity fire increased more with increasing FFDI with previous prescribed fire than with previous wildfire or no fire (Figure 4b).

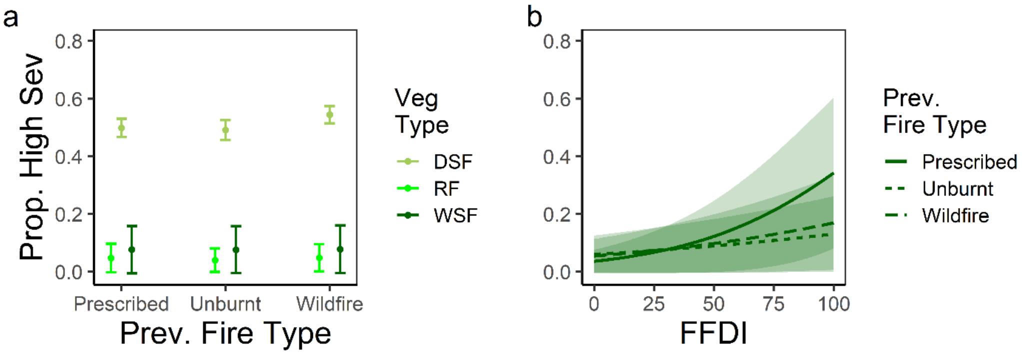

FIGURE 4. MARGINAL EFFECT PLOTS OF A) PREVIOUS FIRE TYPE ON THE AMOUNT OF HIGH SEVERITY IN 2019-20 FOR THREE VEGETATION TYPES: DRY SCLEROPHYLL FOREST, WET SCLEROPHYLL FOREST, AND RAINFOREST, AND B) THE INTERACTION BETWEEN FOREST FIRE DANGER INDEX AND PREVIOUS FIRE TYPE ON THE AMOUNT OF HIGH SEVERITY IN 2019-20 FOR WET SCLEROPHYLL FORESTS. ERROR BARS AND SHADED AREAS REPRESENT 95 % CONFIDENCE.

The dry sclerophyll model for previous fire type explained 11.5 % of the deviance and the null model explained 9.04 % of the deviance. There were no other supported models within 2 AIC. In wet sclerophyll forest, the full model explained 14.6 % of the deviance, and the null model explained 11.4 %. There were no other supported models within 2 AIC. The full model in rainforest explained 35.5 % of the deviance, compared to 29 % in the null model. There was another supported model within 2 AIC which added compound topographic index, which had a significant effect, so it was included in the final model.

Models for previous fire severity

There was significantly more high severity fire in 2019-20 where the severity of previous fires was higher in dry sclerophyll forest (n = 4726). When the severity of the previous fire was low, the proportion of high severity fire was ~ 45 %, compared to ~ 52 % with previous moderate severity fire and ~ 55 % with previous high severity fire. In wet sclerophyll forest (n = 1544) the amount of high severity fire was significantly higher after previous moderate severity fire (~ 35 %) than after previous low severity fire (~ 20 %), while previous high severity fire (~ 27 %) was not significantly different to previous low severity fire (Appendix 2: Table 4, Figure 5). The effect of previous fire severity was not modelled for rainforest due to insufficient data.

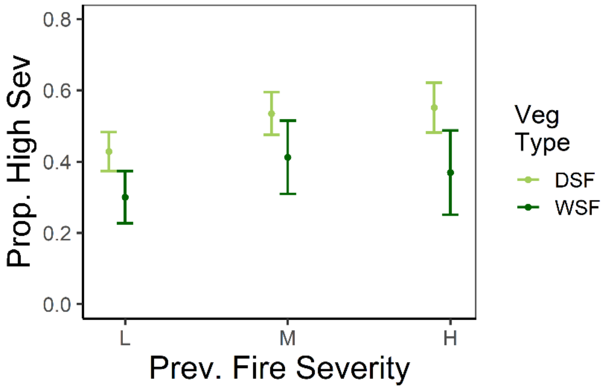

FIGURE 5. MARGINAL EFFECT PLOT OF THE EFFECT OF PREVIOUS FIRE SEVERITY (LOW, MODERATE, AND HIGH) ON THE AMOUNT OF HIGH SEVERITY FIRE IN 2019-20 FOR TWO VEGETATION TYPES: DRY SCLEROPHYLL FOREST AND WET SCLEROPHYLL FOREST. POINTS REPRESENT MEANS AND ERROR BARS ARE 95 % CONFIDENCE.

The model for previous fire severity in dry sclerophyll forest explained 14.3 % of the deviance, compared to 6.88 % in the null model. There were no other supported models within 2 AIC. The only additional variable in the model, which was not in any previous model, was fire frequency, which had a positive effect on the amount of high severity fire (Figure 6). The wet sclerophyll model explained 15.6 % of the deviance, compared to 12.3 % in the null model. There were twelve other supported models within 2 AIC, with two extra variables: road proximity and fire frequency. Neither of these had a significant effect and so were not included in the final model.

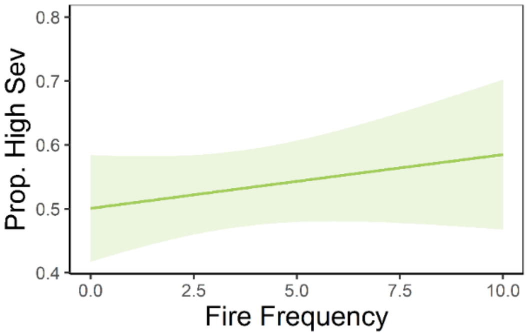

FIGURE 6. THE MARGINAL EFFECT OF FIRE FREQUENCY ON THE AMOUNT OF HIGH FIRE SEVERITY IN 2019-20 IN DRY SCLEROPHYLL FOREST FROM THE MODEL OF PREVIOUS FIRE SEVERITY. SHADED AREA REPRESENTS 95 % CONFIDENCE.

Case studies

The relationship between time since fire and the amount of high severity fire in 2019-20 varied between the seven case study fires. The Gospers Mountain fire and Green Wattle Creek fire both had a similar relationship to that found in dry sclerophyll forest in the full dataset, with significantly less high severity fire in the 0–2-year age class than in the others (Figure 7a & b). In the Ruined Castle fire, the amount of high severity fire was significantly greater in age classes higher than ten years compared to the 0–2-year age class. The 6–10-year age class was not significantly different to the 0–2-year age class, and there was no data in the 3–5-year age class (Figure 7c). In the Carrai East fire, the amount of high severity fire was significantly higher than the 0–2-year age class in the 3–5 and 6–10-year age classes (Figure 7d). Time since fire had no significant effect on the amount of high severity fire in the Border fire or the Currowan 2 fire (Figure 7e & f). In the Carrai Creek fire the amount of high severity fire was greater in the 6–10-year age class than in the 0–2-year age class, while the 11–30 and >50-year age classes had less high severity fire than the 0–2-year age class (Figure 7g). The full model outputs for the case studies can be found in Appendix 2: Table 5 & Table 6.

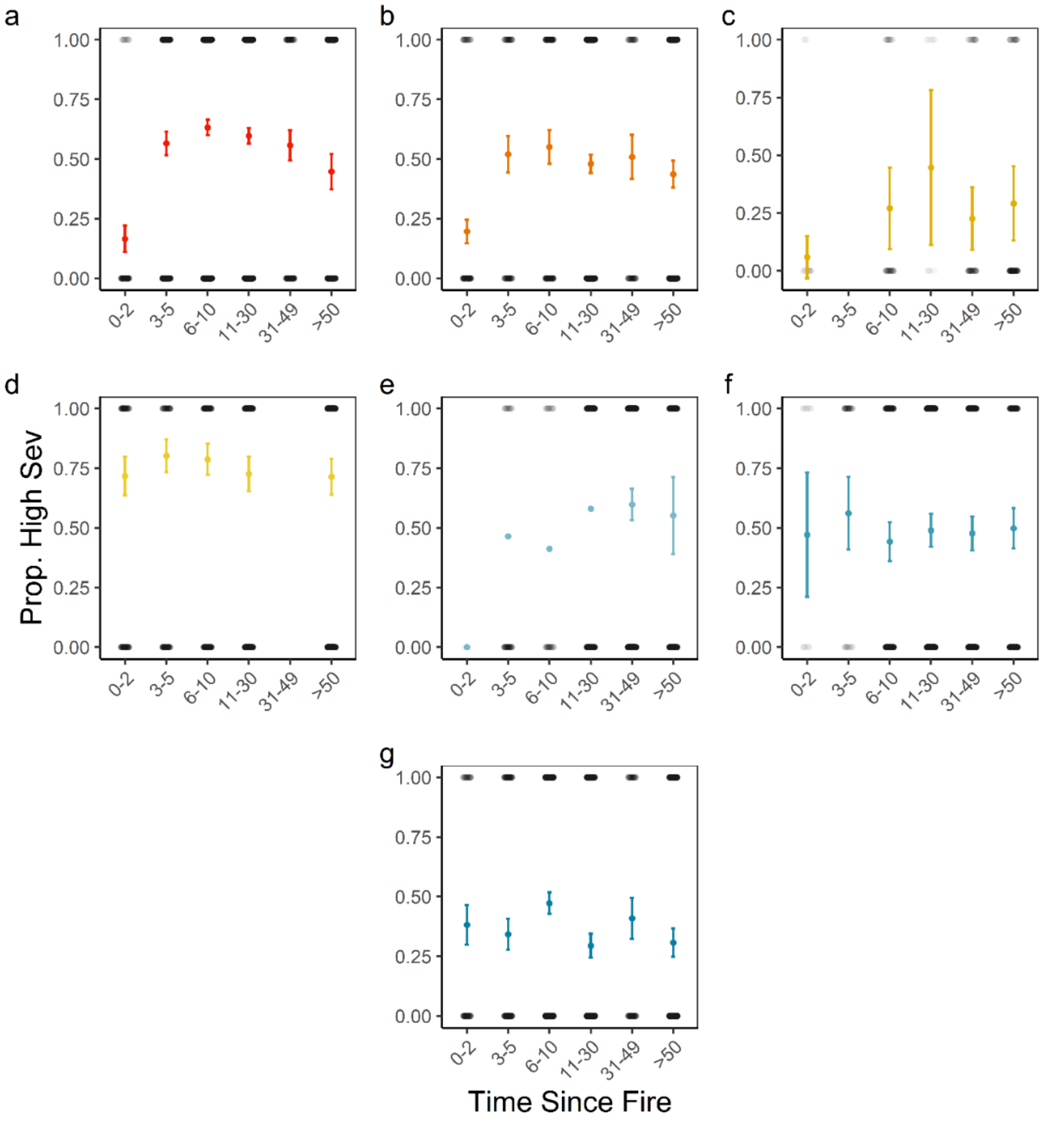

FIGURE 7. MARGINAL EFFECT PLOTS OF THE EFFECT OF TIME SINCE FIRE ON THE AMOUNT OF HIGH SEVERITY FIRE IN 2019-20 FOR SEVEN CASE STUDY FIRES: A) GOSPERS MOUNTAIN, B) GREEN WATTLE CREEK, C) RUINED CASTLE, D) CARRAI EAST, E) BORDER FIRE, F) CURROWAN 2, AND G) CARRAI CREEK. POINTS REPRESENT MEANS AND ERROR BARS ARE 95 % CONFIDENCE. DATA POINTS ARE SHOWN ALONG THE X-AXIS, JITTERED TO SHOW THEIR DENSITY AT EACH LEVEL.

DISCUSSION

Time since fire

There was notably less high severity fire in 2019-20 between the 0-2-year age class and the older age classes in dry sclerophyll forest, and a less clear but still statistically significant difference in wet sclerophyll forest. These results suggest that the effect of time since fire on the severity of a fire is stronger over shorter time scales, perhaps as fuel loads increase back to pre-fire levels, with smaller increases in older forests. This is consistent with previous research on fire severity and behaviour being affected by previous fires, particularly prescribed fire. Recent prescribed fires have previously been found to have led to a reduction in the severity of the 2019-20 fires across different forest types, with areas reburnt in less than one year having the greatest reduction (Hislop et al. 2020). Hislop *et al* (2020) used paired samples to compare prescribed fires from 2015-2019 to previously unburnt areas, while we compared time since fire age classes throughout the whole fire history, including wildfires and prescribed fires. Other studies have found that prescribed fires up to five years prior to wildfire are effective in reducing fire severity and spread (Price and Bradstock 2012, Tolhurst and McCarthy 2016). Our results show an increase in high severity fire in dry sclerophyll forests up to 10 years since the previous fire before a slight drop and plateau in older age classes. Similar trends have been found in previous studies. A study in dry sclerophyll forests found that the chance of crown fire increased up to ten years post-fire before declining in older age classes (Storey et al. 2016). Multiple studies in Eucalypt forests have also found that elevated fuels recover rapidly after fire before declining over longer periods (Gordon et al. 2017, Dixon et al. 2018, Zylstra 2018, McColl-Gausden and Penman 2019, Volkova et al. 2019, McColl-Gausden et al. 2019).

The variation in fire severity over the whole fire footprint was not well captured by the models of time since fire that we used in this study. This suggests that there were other important factors driving variation in the fires, or that some of the variables used in the study were not at a sufficiently fine scale to detect landscape variation. Fire weather has been reported as a key factor which determined the fire behaviour in 2019-20 (Nolan et al. 2020, Davey and Sarre 2020, Deb et al. 2020) and we also found a positive relationship between FFDI and the amount of high severity fire. The weather data we used for this study was the maximum FFDI over each stage of fire progression from the nearest weather station (Williamson and Price 2020). Many of the burnt areas are several kilometres from the nearest weather station, meaning there could be local variation in weather conditions which were not detected in the data. There would also have been variation in the weather over each progression period, which varied in length depending on the rate of spread of the fire and the availability of data. The progression polygons used to assign weather had a median length of seventeen hours. The progression of large runs of fire over short periods of time could not be mapped in detail, so any changes in weather during those times may not be represented in the data.

The amount of high severity fire in 2019-20 decreased as the live fuel moisture content increased. Live fuel moisture content is the measured moisture content in live vegetation at the landscape scale. Fuel moisture is a key driver of fire behaviour in southeast Australian forests as it determines the availability of fuel to burn (Bradstock 2010, Cheney et al. 2012).

Slope negatively affected the amount of high severity fire in wet and dry sclerophyll forests, despite a general assumption that fire intensity and severity increase with slope due to the alignment of flame angle and fuel structure. Several previous studies have found a negative relationship between slope and fire severity in dry sclerophyll forests and attribute it to fuel discontinuity on steeper slopes (Bradstock et al. 2010, Storey et al. 2016, Barker and Price 2018).

Since it is a measure of vegetation consumption, fire severity is strongly determined by canopy height and structure. Shorter canopies can experience high fire severity with shorter flame heights than taller canopies. While the different forest types we analysed have generally different canopy heights (i.e., wet sclerophyll forests are taller than dry sclerophyll forests), fine scale variation in vegetation structure was not part of the data and may have resulted in differences in fire severity within forest types.

Previous fire type

The amount of high severity fire in 2019-20 was significantly higher after previous wildfire than after previous prescribed fire or in previously unburnt areas in dry sclerophyll forests. In wet sclerophyll forests there was more high severity fire with previous wildfire and unburnt areas than with previous prescribed fire. The size of these differences was small and there was no difference between the three fire types in rainforest. These results indicate that prescribed fire may reduce the risk of high severity fire compared to wildfires or no fire, but the reduction is small.

There was an interaction between previous fire type and FFDI in wet sclerophyll forest. The increase in high severity fire as FFDI increased was stronger if the previous fire was a prescribed fire.

Previous fire severity

Including previous fire severity improved the amount of variation explained by the models and significantly influenced the amount of high severity fire in 2019-20. In wet and dry sclerophyll forests the amount of high severity fire was lowest after previous low severity fire, and higher after previous moderate and high severity fire. This is comparable to the fire severity relationships found previously for reburns in southeast Australia (Barker and Price 2018, Collins et al. 2021b) and likely the result of increased vertical fuel continuity, due to resprouting trees and shrubs and new recruits, and a shorter canopy height after higher severity fire (Bennett et al. 2016, Bassett et al. 2017, Karna et al. 2020). Unlike the two previous studies, we found that the amount of high severity fire in wet sclerophyll forest was greatest after moderate previous fire severity. This could be because moderate fire severity is enough to promote regeneration in the trees and understory but not to completely consume the canopy. This would allow for a faster recovery of surface fuel loads as the trees drop their leaves. With high severity fire, the canopy would be greatly reduced for some time.

Case studies

The identities of each individual fire within the 2019-20 fire season were included as a random effect in each of the models presented above. The size of this effect was quite large, suggesting that the modelled relationships varied between each fire. Because of this, we also examined seven fires from the fire season in separate models.

The relationship between time since fire and the amount of high severity fire in 2019-20 varied between case study fires. Only two fires, the Gospers Mountain and Green Wattle Creek fires, had similar time since fire relationships to the whole landscape model in dry sclerophyll model. This may be because they were two of the largest fires of the season and had a high proportion of dry sclerophyll forest. The Carrai East fire had a similar relationship, but the amount of high severity fire was not significantly greater in the older age classes, though this may be due to a lack of data (Appendix 1: Figure 11), and the Ruined Castle fire was also similar but with more variation in each age class. There was no effect of time since fire in the Border and Currowan 2 fires. The differences between each of the case study fires is likely due to local variation in climate, weather, and fuel structure that was not captured in the data used for this study. Rapid weather driven expansion of the fires would not have been detected and could have overwhelmed the other variables. We also did not consider any suppression activity which may have altered fire behaviour or severity. More detailed case studies will be required to examine the variation in fire severity and behaviour between the 2019-20 fires in greater depth.

CONCLUSION

The 2019-20 fire season was largely driven by low fuel moisture due to drought, and the weather at the time of the fires (Nolan et al. 2020). We did, however, detect an effect of time since fire on the severity of the 2019-20 fires. If an area was reburned within two years of the last fire, there was less high severity fire than in older age classes. The amount of high severity fire was also less after previous prescribed fire than previous wildfire in dry sclerophyll forests, which is the most widespread vegetation type in the area. There was more high severity fire if the previous fire burnt with moderate or high severity, matching previously found relationships (Barker and Price 2018, Collins et al. 2021b).

Previous prescribed fires covered a relatively small area of the 2019-20 fire footprint, so any effects on the severity of those fires at a landscape scale would necessarily be small. This does not mean that prescribed fires had no effect on the subsequent wildfires, it is simply a matter of scale. Individual prescribed fires likely altered the spread or intensity of fire fronts enough to allow firefighters to perform active suppression or construct containment lines.

Our results indicate that while a landscape scale approach such as ours is important to observe general trends in fire, it is also necessary to examine smaller scales to determine local variation and effects which can be drowned out at larger scales. To facilitate this, we would need higher resolution spatial and temporal data to document variation in weather, fuel structure, and fire spread.

ACKNOWLEDGEMENTS

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APPENDIX 1 – DATA DISTRIBUTIONS

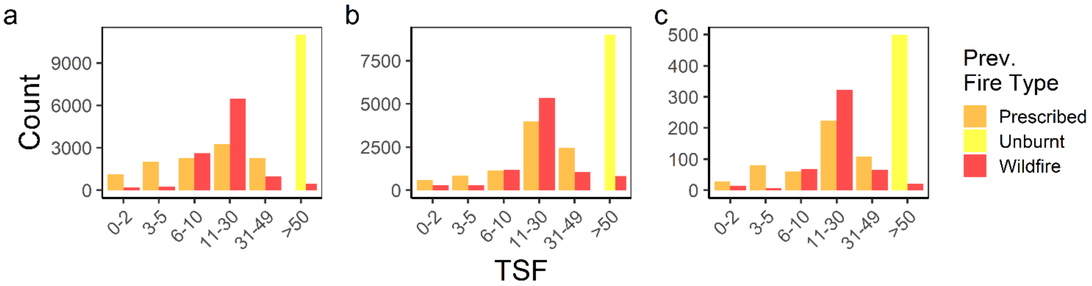


FIGURE 8. THE DISTRIBUTION OF TIME SINCE FIRE FOR EACH PREVIOUS FIRE TYPE IN A) DRY SCLEROPHYLL FOREST, B) WET SCLEROPHYLL FOREST, AND C) RAINFOREST. NOTE THE DIFFERENT SCALES OF THE Y-AXES.

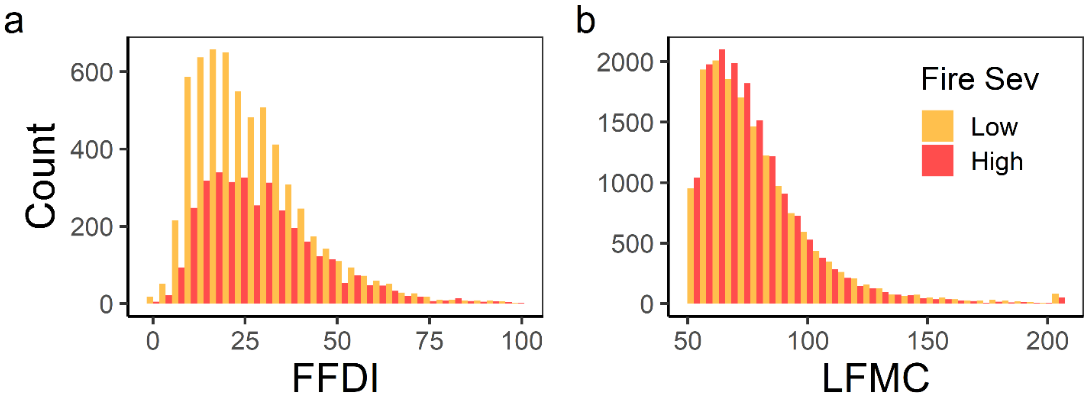


FIGURE 9. THE DISTRIBUTION OF A) FOREST FIRE DANGER INDEX, AND B) LIVE FUEL MOISTURE CONTENT FOR HIGH AND LOW FIRE SEVERITY IN 2019-20.

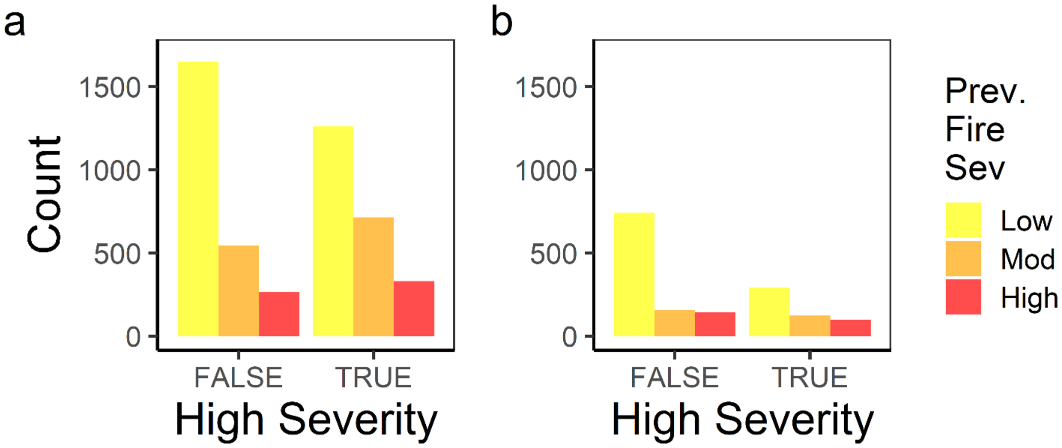


FIGURE 10. THE DISTRIBUTION OF FIRE SEVERITY IN 2019-20 FOR EACH PREVIOUS FIRE SEVERITY CLASS FOR A) DRY SCLEROPHYLL FOREST, AND B) WET SCLEROPHYLL FOREST.

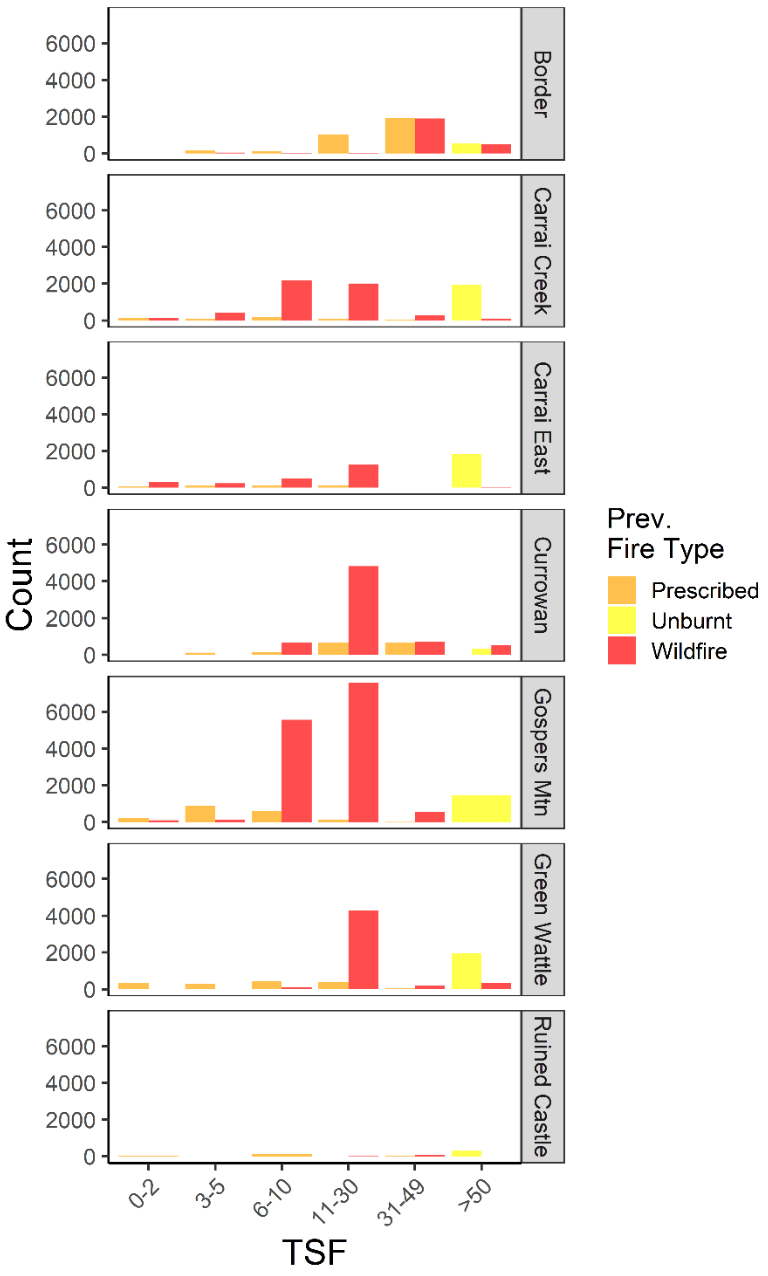


FIGURE 11. THE DISTRIBUTION OF TIME SINCE FIRE FOR EACH PREVIOUS FIRE TYPE FOR THE SEVEN CASE STUDY FIRES.

APPENDIX 2 – MODEL OUTPUTS

Model	Variable	Estimate	SE	z	Pr
DSF	3-5 TSF	7.58E-01	8.10E-02	9.365	< 0.001
	6-10 TSF	1.03E+00	7.33E-02	14.047	< 0.001
	11-30 TSF	9.24E-01	7.00E-02	13.206	< 0.001
	31-49 TSF	6.95E-01	8.04E-02	8.641	< 0.001
	≥ 50 TSF	6.75E-01	7.08E-02	9.533	< 0.001
	Slope	-2.91E-02	1.44E-03	-20.222	< 0.001
	MAP	-8.36E-03	1.15E-03	-7.247	< 0.001
	MAT	-6.35E-01	8.22E-02	-7.723	< 0.001
	FFDI	1.64E-02	7.32E-04	22.403	< 0.001
	(Log) LFMC	-4.92E-01	5.15E-02	-9.559	< 0.001
	MAP*MAT	6.29E-04	7.96E-05	7.899	< 0.001
WSF	3-5 TSF	0.424468	0.106869	3.972	< 0.001

	6-10 TSF	0.519322	0.095092	5.461	< 0.001
	11-30 TSF	0.38778	0.086647	4.475	< 0.001
	31-49 TSF	0.109257	0.095089	1.149	0.251
	≥ 50 TSF	0.290006	0.08656	3.35	< 0.001
	Slope	-0.00878	0.00191	-4.598	< 0.001
	MAP	-0.00116	0.000201	-5.765	< 0.001
	FFDI	0.015276	0.000766	19.949	< 0.001
	(Log) LFMC	-0.945	0.057506	-16.433	< 0.001
	(Log) TSL	-0.14627	0.021187	-6.904	< 0.001
	CTI	-0.07301	0.010102	-7.228	< 0.001
RF	3-5 TSF	-1.21	0.667241	-1.813	0.0698
	6-10 TSF	-0.16225	0.498762	-0.325	0.745
	11-30 TSF	-0.60922	0.445376	-1.368	0.171
	31-49 TSF	-1.05942	0.503258	-2.105	0.0353
	≥ 50 TSF	-0.86657	0.452244	-1.916	0.0553
	Aspect	-0.00117	0.000995	-1.179	0.239
	MAP	-0.00151	0.001427	-1.056	0.291
	MAT	0.362321	0.12499	2.899	0.00375
	FFDI	0.016183	0.004231	3.825	< 0.001
	(Log) LFMC	-1.11234	0.351211	-3.167	0.00154

TABLE 1: OUTPUTS FOR THE LINEAR MIXED-EFFECTS MODELS OF TIME SINCE FIRE IN DRY SCLEROPHYLL FOREST, WET SCLEROPHYLL FOREST, AND RAINFOREST.

Model	Variable	Estimate	SE	z	Pr
DSF	Unburnt	-5.53E-02	3.69E-02	-1.498	0.134
	Wildfire	1.50E-01	3.24E-02	4.639	< 0.001
	Slope	-2.93E-02	1.43E-03	-20.412	< 0.001
	MAP	-7.80E-03	1.15E-03	-6.788	< 0.001
	MAT	-5.90E-01	8.19E-02	-7.213	< 0.001
	FFDI	1.61E-02	7.29E-04	22.139	< 0.001
	(Log) LFMC	-4.85E-01	5.13E-02	-9.463	< 0.001
	MAP*MAT	6.00E-04	7.93E-05	7.575	< 0.001
WSF	Unburnt	0.552616	0.075508	7.319	< 0.001
	Wildfire	0.496947	0.074036	6.712	< 0.001
	FFDI	0.026051	0.001297	20.079	< 0.001
	(Log) TSL	-0.14737	0.021206	-6.95	< 0.001
	MAP	-0.00115	0.000201	-5.751	< 0.001
	(Log) LFMC	-0.95328	0.057551	-16.564	< 0.001
	CTI	-0.05423	0.0091	-5.96	< 0.001
	Unburnt*FFDI	-0.0178	0.001813	-9.814	< 0.001
	Wildfire*FFDI	-0.01492	0.001779	-8.385	< 0.001
RF	Unburnt	-0.2219	0.268208	-0.827	0.408
	Wildfire	0.168519	0.228819	0.736	0.461
	FFDI	0.015059	0.004237	3.554	< 0.001
	Aspect	-0.00129	0.000997	-1.291	0.197
	MAP	-0.00144	0.001434	-1.003	0.316
	MAT	0.377391	0.126006	2.995	0.00274
	(Log) LFMC	-1.20966	0.349507	-3.461	< 0.001
	CTI	-0.13912	0.046595	-2.986	0.00283

TABLE 2: OUTPUTS FOR THE LINEAR MIXED-EFFECTS MODELS OF PREVIOUS FIRE TYPE DRY SCLEROPHYLL FOREST, WET SCLEROPHYLL FOREST, AND RAINFOREST.

Model	Variable	Estimate	SE	z	Pr
DSF	Mod Severity	0.333262	0.076548	4.354	< 0.001
	High Severity	0.500176	0.112312	4.453	< 0.001
	3-5 TSF	1.974946	0.35951	5.493	< 0.001
	6-10 TSF	1.350654	0.320018	4.221	< 0.001
	11-30 TSF	1.204856	0.310461	3.881	< 0.001
	31-49 TSF	0.612915	0.480411	1.276	< 0.001
	≥ 50 TSF	-0.06642	0.004615	-14.394	0.202
	Slope	-0.14059	0.027044	-5.199	< 0.001
	CTI	0.024423	0.002645	9.235	< 0.001

	FFDI	0.068474	0.033345	2.054	< 0.001
	Fire Frequency	-0.00108	0.000898	-1.208	0.0400
	MAP	-0.59503	0.098031	-6.07	0.227
	MAT	0.333262	0.076548	4.354	< 0.001
WSF	Mod Severity	0.702564	0.171759	4.09	< 0.001
	High Severity	0.33561	0.220501	1.522	0.128
	3-5 TSF	2.696533	1.194743	2.257	0.0240
	6-10 TSF	2.495485	0.963039	2.591	0.00956
	11-30 TSF	1.753494	0.941193	1.863	0.0625
	31-49 TSF	2.540801	1.609876	1.578	0.115
	Slope	-0.03282	0.008673	-3.784	< 0.001
	(Log) TSL	0.488004	0.318368	1.533	0.125
	CTI	-0.06659	0.039722	-1.676	0.0937
	FFDI	0.020293	0.00471	4.308	< 0.001
	(Log) LFMC	-0.75499	0.261344	-2.889	0.00387
	MAP	-0.00126	0.000913	-1.386	0.166
	MAT	-0.42723	0.11246	-3.799	< 0.001

TABLE 3: OUTPUTS FOR THE LINEAR MIXED-EFFECTS MODELS OF PREVIOUS FIRE SEVERITY IN DRY SCLEROPHYLL FOREST AND WET SCLEROPHYLL FOREST.

Model	Variable	Estimate	SE	z	Pr
Gospers Mountain	CTI	-0.20668	0.014082	-14.676	< 0.001
	FFDI	0.032389	0.001675	19.339	< 0.001
	Fire Frequency	0.043761	0.019957	2.193	0.0283
	MAP	-0.00409	0.000918	-4.454	< 0.001
	MAT	-1.10741	0.130771	-8.468	< 0.001
	Slope	-0.07907	0.002585	-30.591	< 0.001
	3-5 TSF	1.880213	0.20505	9.17	< 0.001
	6-10 TSF	2.157212	0.196879	10.957	< 0.001
	11-30 TSF	2.008227	0.193917	10.356	< 0.001
	31-49 TSF	1.845191	0.221373	8.335	< 0.001
	≥ 50 TSF	1.403341	0.234106	5.994	< 0.001
	RF	-1.89636	0.241728	-7.845	< 0.001
	WSF	-1.17469	0.066172	-17.752	< 0.001
Green Wattle Creek	FFDI	0.03011	0.001919	15.688	< 0.001
	3-5 TSF	1.489783	0.190677	7.813	< 0.001
	6-10 TSF	1.613826	0.179286	9.001	< 0.001
	11-30 TSF	1.330246	0.143035	9.3	< 0.001
	31-49 TSF	1.444897	0.215846	6.694	< 0.001
	≥ 50 TSF	1.155174	0.153176	7.541	< 0.001
	MAP	-0.04679	0.004526	-10.337	< 0.001
	MAT	-3.67661	0.3126	-11.761	< 0.001
	Slope	-0.03601	0.002879	-12.506	< 0.001
	RF	-1.84178	0.313443	-5.876	< 0.001
	WSF	-0.30767	0.083312	-3.693	< 0.001
	MAP*MAT	0.003526	0.000355	9.924	< 0.001
Ruined Castle	FFDI	3.03E-02	1.08E-02	2.812	0.00492
	6-10 TSF	1.78E+00	9.16E-01	1.938	0.0526
	11-30 TSF	2.55E+00	9.90E-01	2.579	0.00992
	31-49 TSF	1.53E+00	7.71E-01	1.989	0.0467
	≥ 50 TSF	1.88E+00	9.14E-01	2.055	0.0399
	(Log) LFMC	3.77E-01	3.81E-01	0.989	0.322
	Fire Frequency	3.64E-01	2.40E-01	1.516	0.130
	MAP	3.21E-03	1.76E-03	1.824	0.0682
	Slope	-4.01E-02	1.21E-02	-3.316	< 0.001
	RF	-2.85E+01	3.59E+05	0	1
	WSF	-2.10E+00	7.66E-01	-2.741	0.00613
Carrai East	CTI	-0.1737	0.024373	-7.127	< 0.001
	FFDI	0.0188	0.002559	7.346	< 0.001
	3-5 TSF	0.467457	0.17807	2.625	0.00866
	6-10 TSF	0.378308	0.151952	2.49	0.0128
	11-30 TSF	0.040886	0.137965	0.296	0.767
	≥ 50 TSF	-0.01413	0.136061	-0.104	0.917

	(Log) LFMC	-1.00781	0.148472	-6.788	< 0.001
	MAP	-0.01541	0.009913	-1.554	0.120
	MAT	-1.08107	0.828464	-1.305	0.192
	RF	-1.42376	0.162336	-8.77	< 0.001
	WSF	-0.4002	0.099217	-4.034	< 0.001
	MAP*MAT	0.000366	0.00056	0.653	0.514

TABLE 4: OUTPUTS FOR THE LINEAR MIXED-EFFECTS MODELS OF TIME SINCE FIRE FOR THE SEVEN CASE STUDY FIRES.

Model	Variable	Estimate	SE	z	Pr
Border Fire	FFDI	1.97E-02	2.76E-03	7.133	< 0.001
	3-5 TSF	3.72E+02	4.75E+07	0	1
	6-10 TSF	3.72E+02	4.75E+07	0	1
	11-30 TSF	3.72E+02	4.75E+07	0	1
	31-49 TSF	3.73E+02	4.75E+07	0	1
	≥ 50 TSF	3.72E+02	4.75E+07	0	1
	(Log) LFMC	-7.28E-01	1.30E-01	-5.602	< 0.001
	Slope	1.67E-02	4.87E-03	3.419	< 0.001
	MAP	5.38E-03	1.26E-02	0.426	0.670
	MAT	9.74E-02	8.63E-01	0.113	0.910
	RF	1.23E-01	3.05E-01	0.403	0.687
	WSF	1.40E-01	6.57E-02	2.135	0.0328
	MAP*MAT	-4.21E-04	1.15E-03	-0.366	0.714
Currowan 2	Aspect	-0.00087	0.000269	-3.23	0.00124
	CTI	-0.09663	0.021568	-4.48	< 0.001
	FFDI	0.011154	0.001517	7.354	< 0.001
	3-5 TSF	0.362184	0.594035	0.61	0.542
	6-10 TSF	-0.11647	0.527059	-0.221	0.825
	11-30 TSF	0.073775	0.518921	0.142	0.887
	31-49 TSF	0.021567	0.525846	0.041	0.967
	≥ 50 TSF	0.107324	0.52816	0.203	0.839
	(Log) TSL	-0.24999	0.05617	-4.451	< 0.001
	Slope	-0.04742	0.004285	-11.064	< 0.001
	RF	-1.81779	0.219173	-8.294	< 0.001
	WSF	-0.53882	0.069858	-7.713	< 0.001
Carrai Creek	CTI	-0.14826	0.021077	-7.034	< 0.001
	(Log) LFMC	-1.64436	0.163321	-10.068	< 0.001
	MAP	-0.00803	0.001566	-5.125	< 0.001
	MAT	0.184408	0.0489	3.771	< 0.001
	3-5 TSF	-0.17203	0.184803	-0.931	0.352
	6-10 TSF	0.371987	0.153903	2.417	0.0156
	11-30 TSF	-0.3927	0.156042	-2.517	0.0118
	31-49 TSF	0.111731	0.202466	0.552	0.581
	≥ 50 TSF	-0.33084	0.165992	-1.993	0.0462
	(Log) TSL	-0.6555	0.109031	-6.012	< 0.001
	Slope	-0.04832	0.003366	-14.355	< 0.001
	RF	-1.78841	0.146773	-12.185	< 0.001
	WSF	-0.5091	0.082525	-6.169	< 0.001

TABLE 5: OUTPUTS FOR THE LINEAR MIXED-EFFECTS MODELS OF TIME SINCE FIRE FOR THE SEVEN CASE STUDY FIRES, CONT.

4. EFFECTS OF PRESCRIBED FIRE ON FIRE BEHAVIOUR IN THE 2019-20 FIRE SEASON

INTRODUCTION

In the previous section, we conducted statistical analysis of tens of thousands of points across the landscape to determine what effect previous burning had on the occurrence of high severity fire in the 2019/20 bushfires. We found that previous prescribed burning caused a small reduction in high severity and only if the burn had occurred in the previous few years. This is a similar approach to many studies of previous bushfires, which all found broadly similar results (Bradstock *et al.* 2010); Storey *et al.* (2016); (Tolhurst and McCarthy 2016). However, that approach does not directly address the question of whether a particular prescribed burn was useful in the context of risk reduction, i.e. gave some advantage to firefighters. In this section, we address this question by focusing on the scale of each prescribed burn and its effect on measures of fire behaviour that can be determined from mapped post-fire data. This approach has some history (Rawson *et al.* 1985; Underwood *et al.* 1985; Grant and Wouters 1993) as case studies of individual fires. After the 2019/20 fires, Pedroza *et al.* (2020) examined the effect of the most recent 13 prescribed burns in the Nattai National Park on the Green Wattle fire. Their interpretation was that the burns substantially reduced the extent of canopy scorch but burns more than two years old were less effective. Useful though these kinds of studies are, they target a small subset of the burns, which limits confidence in the learnings. In this study, we examined all 509 burns from 2014 onwards that were encountered by the 2019/20 bushfires. This comprehensive approach has no possible sampling bias, and is large enough to conduct statistical analysis of the patterns. In this respect, the study is comparable to Hislop *et al.* (2020) who studied 300 burns >200 ha in NSW and Victoria encountered by the 2019/20 bushfires. They found that 48% of burns reduced fire severity and 66% of burns less than a year old at the time of encounter.

There is a hierarchy of potential effects that a prescribed burn can have:

1) The strongest effect is to stop the bushfire altogether. Here, the prescribed burn is aligned with the final bushfire boundary.
2) It may allow the bushfire to burn around it but leaving an unburnt shadow in its wake. The prescribed burn is well within the bushfire perimeter, but there are unburnt areas within or around it.
3) It may stop the bushfire internally (either entirely or by leaving unburnt 'islands' within the burn), but the bushfire burns around or through.
4) It may reduce the severity of the bushfire. This reflects two related effects: the bushfire intensity is lower meaning that fire suppression is more achievable; and rate of spread slows, giving firefighters more time to plan the next phase of suppression. Fire severity on its own cannot be used to infer rate of spread so any such effect can only be implied.

These effects may solely be due to the prescribed burn, or they may be the result of fire suppression occurring in or around them. Firefighters use prescribed burns to gain an advantage over the bushfire, which may be by backburning into the burn, away from the burn, strengthening mechanical control lines along the burn perimeter, re-directing the bushfire path or buying time for suppression somewhere else. This is most likely the explanation for cases where the bushfire perimeter is aligned with a prescribed burn, especially where that perimeter is along a road which gives firefighters access. Since post-fire mapping does not include information on suppression activity, it cannot quantify exactly what advantage was gained by the burn or the extent to which the burn as opposed to firefighters was responsible for the advantage. Such an understanding would require cross analysis of the mapping with detailed information from firefighters about what was happening on the ground. It is hoped that in future, such a cross-matching could be done through a routine lessons learned process whereby firefighters would document what they observed when the bushfire met the prescribed burn. This information is built into the design of the fire-meets-fire database in this project. The current DPIE APR Interview project aim to improve this interview-based documentation (Wilkinson 2021). For this study, which aims to determine what can be learned from available GIS information, we cross-reference to the interviews where available.

METHODS

Data

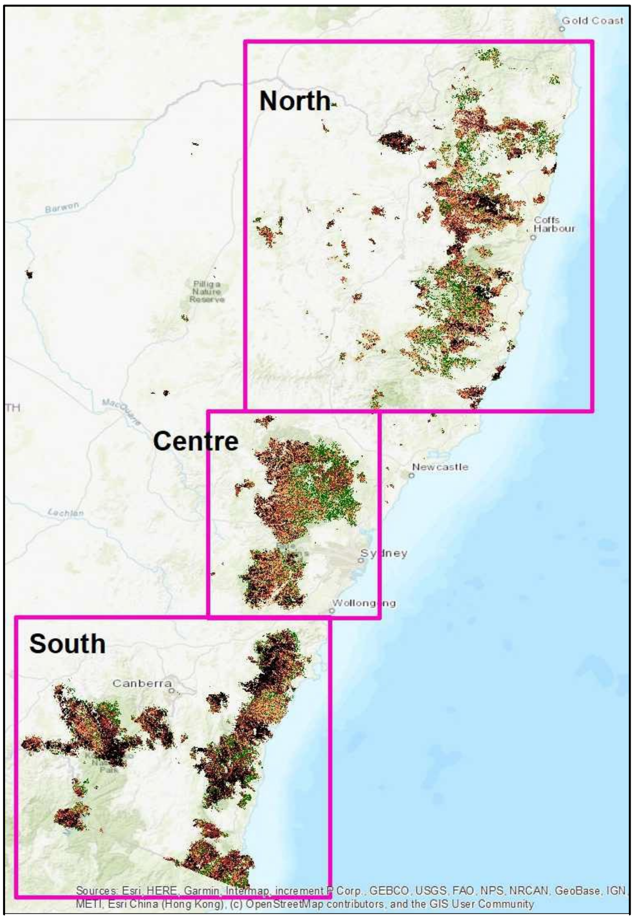
Data for the project were sourced mainly from DPIE, consisting of burn perimeters and fire severity of the subsequent bushfires (Table 5.1). Wind direction was sourced from a bushfire progression layer created by the authors for the NSW Bushfire Inquiry (Price and Williamson 2020), through a process of editing progression data from the Rural Fire Service and matching each polygon with hourly Bureau of Meteorology data.

Dataset	Description	Source
Prescribed Burn History	Boundaries of prescribed burns from 2014 to 2019, with names and start date	DPIE
Fire Severity (FESM) for 2019/20 bushfires	Fire Extent and Severity Mapping from sentinel satellite imagery	DPIE
Wind Direction	Wind direction at the closest BOM weather station, derived from a progression map used for the NSW 2019/20 Bushfire Inquiry reports by the NSW BRMR Hub. i.e. each polygon in the progression data has an assigned wind direction.	University of Wollongong from original data from RFS and BOM
Interview reports	From the APR Intern project (for cross-checking)	Pers. Comm.

TABLE 5.1. DATA SOURCES FOR THIS ANALYSIS.

Steps

First, the prescribed burns were filtered to those inside or touching the extent of the 2019/20 fires, giving 509 burns, and we examined all of these. The wind direction was determined visually by overlaying it on the progression map and inspecting the wind speed in the progression polygons within and nearby the burn. Next, the burn perimeter was overlayed on the severity map. Using the determined wind direction, we visually determined three hierarchical levels of changes to bushfire behaviour: whether the burn caused an unburnt shadow downwind of it, stopped within the burn (but without leaving a shadow) or



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

FIGURE 5.1. REGIONS USED IN THIS STUDY.

reduced the bushfire severity. Our definition of stopping simply means there were unburnt patches within the burn perimeter. The definition of a shadow was where there was an unburnt or low severity burning immediately downwind of the burn, whether or not the fire also stopped in the burn. Sometimes there were more than one progression polygon within the burn or several with differing wind directions in the vicinity, which made confidence in the wind direction low, and hence also affected confidence in fire behaviour measures. Also, sometimes it was difficult to be definitive about whether there was a severity reduction (depending on the magnitude of the reduction). Therefore, the confidence in each behaviour was also recorded, as low, medium or high. We analysed the data according to region and burn age and burn area, including conducting a binomial regression models of whether burns stopped or reduced severity (separate models for each) with burn age, burn area and region as the predictors. The regions were north, centre or southern with the boundary between north and central (Figure 5.1) being the north of Wollemi National Park (Gospers bushfire), and the boundary between central and south being Mossvale (between Green Wattle and Currowan bushfires). We also identified the fire management zone for each burn where it was provided in the name. This identified 152 Strategic Fire Advantage Zone (SFAZ) burns and 162 Landscape Management Zone (LMZ) burns, but zone information was not available for 195 (38%) so zone was not used in the statistical analysis.

We cross-checked our interpretations against the APR interviews to assess whether this GIS approach matched what firefighters experienced on the ground. Also, we cross-checked our results with a study of 13 recent burns from the Nattai National Park (Pedroza et al 2020). This process caused us to modify our methods. There were cases where it the wind was blowing away from the burn and so we assumed that no effect could occur, whereas the interviews suggested that the fires were in fact burning into the burn (presumably as a backing fire) and the burn did reduce fire behaviour. Therefore we assumed burns aligned with a fire boundary to be stopping the fire, unless the boundary was obviously caused by a landscape feature such as the ocean. We assigned low confidence if the wind was blowing the fire away.

RESULTS

General results

Of 1699 burns in the DPIE estate from 2014-2019, 509 or 30% were encountered by the 2019/20 bushfires. Those 509 were distributed fairly evenly across years (from 47 in 2018 to 159 in 2016) and mean area (from 359 ha in 2015 to 714 ha in 2019) (Table 5.2), the largest number were from 2016 and the largest mean area was in 2019. The APR Interviews highlighted some cases where the burn provided an advantage but we did not observe it. There were three cases where the bushfire stopped in the burn for several days before proceeding, allowing firefighters time to strengthen containment lines or focus on property protection (Colo Heights, Left Arm Creek, Bala Range Pt 2). We recorded no effect for two of these and a severity reduction for the third (Left Arm Creek). There were also two burns that were outside the bushfire boundary that held up spotfires (Pitsgah Ridge and MacMahons). We recorded no effect for either of these. Other cases that we cross-referenced are described in the following sections.

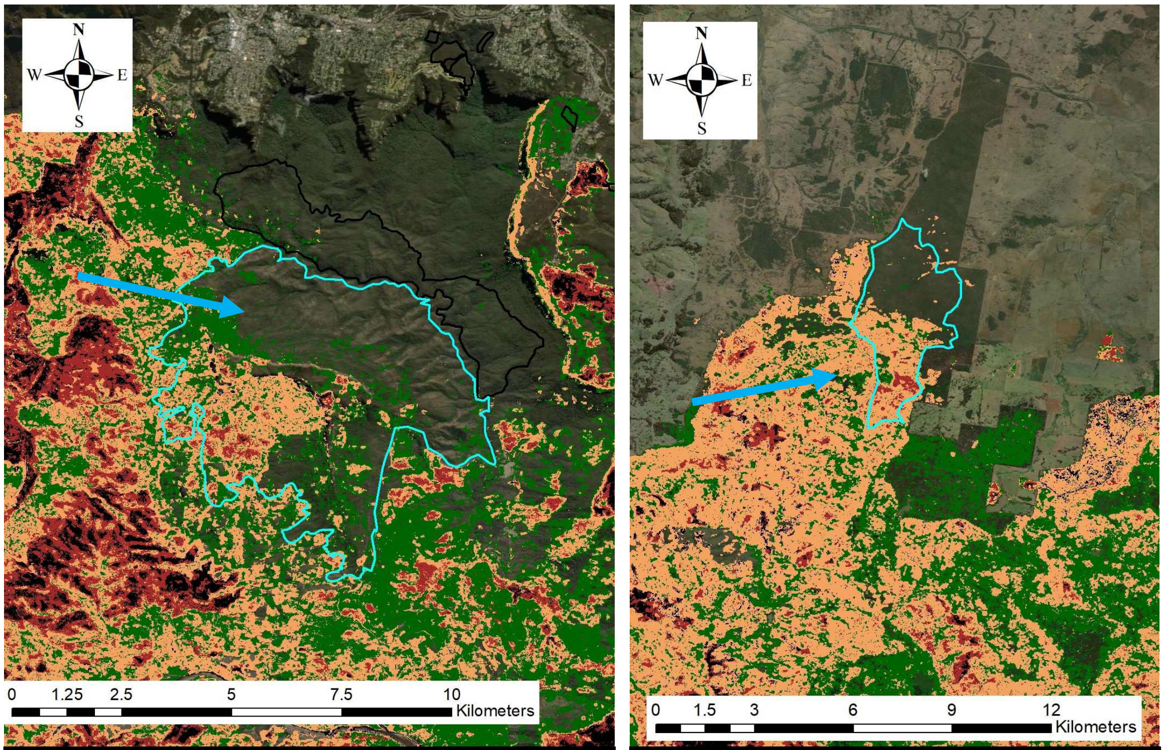
Year	# of Burns	Mean area (ha)
2014	73	535
2015	106	359
2016	159	424
2017	54	525
2018	47	684
2019	70	714

TABLE 5.3. NUMBERS AND MEAN AREA OF PRESCRIBED BURNS ENCOUNTERED BY THE 2019/20 BUSHFIRES BY YEAR OF BURN.

Stopping the fire

There were 68 instances of a prescribed burn being on the boundary of a bushfire, an effectiveness of 13.4%. Only 21 of these were considered high confidence because there was often uncertainty about whether the fire was petering out anyway (see Figure 5.2 for an example of high and medium confidence). Most of the cases were not accompanied by unburnt patches within the burn (42) and 31 showed no severity reduction (see below). The 68 cases were distributed evenly across years and were actually more common in the older 2014 burns (Figure 5.3). They were also more common in the central region and in larger burns (Figure 5.3). The statistical analysis suggested that boundary stopping was more likely in larger burns and in the central region (Table 5.3a), but year did not affect stopping likelihood.

The APR interviews covered two of these events. The northern edge of the Green Wattle fire approached the Mount Solitary burn (implemented August 2018) on December 5th 2019 and did not spread beyond it (Figure 5.2). Firefighters explained that bushfire “slammed” into the burn and then trickled from then onwards. The Wooloweyah burn was mentioned in the methods. This one was described as stopping the Shark Creek 2 bushfire as it ran ‘hard’ toward houses.



Mt Solitary Ck May 2018, Green Wattle Fire, Border Stop, High confidence.

WALC- Dog Trap Ck Aug 2018, Mummel Fire , Border Stop, Medium confidence.

FIGURE 5.2. TWO EXAMPLES HR BURNS IN WHICH THE SUBSEQUENT BUSHFIRES BOUNDARY ALIGNED WITH THE HR. THE ARROW INDICATES THE WIND DIRECTION.

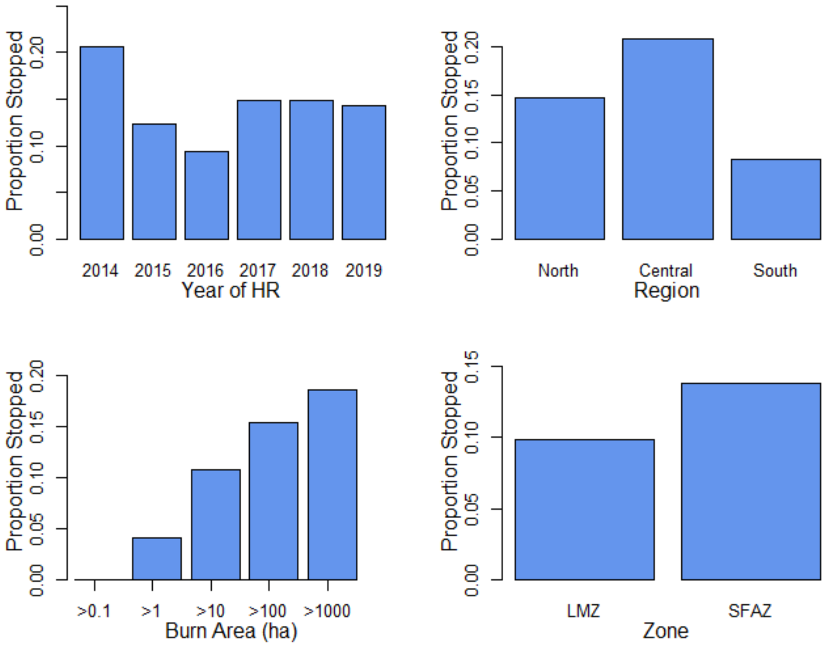
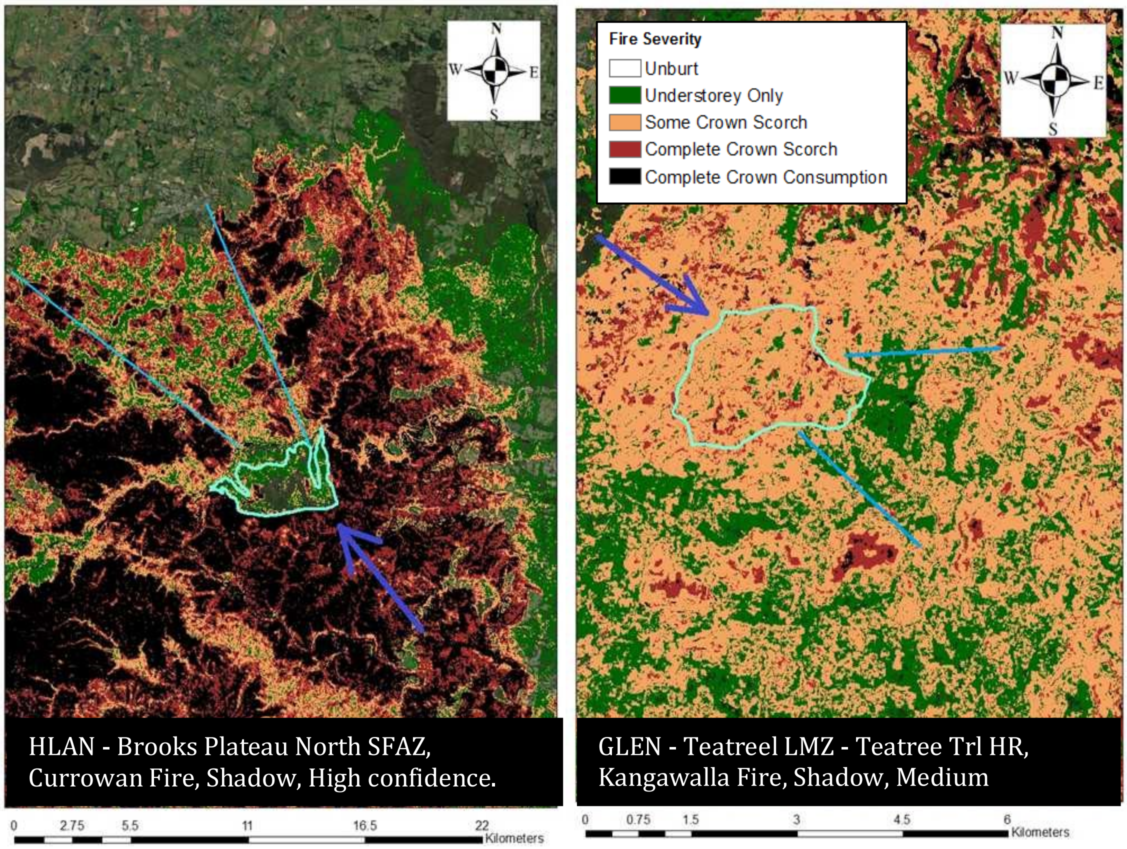


FIGURE 5.3. THE PROPORTION OF THE 509 BURNS THAT ALIGNED WITH THE BUSHFIRE BOUNDARY, GROUPED BY YEAR OF BURN, REGION, BURN AREA AND ZONE.

Shadows

Only two burns caused an unburned shadow. The first was the Brookes Plateau North SFAZ, which was implemented in February 2019 and was encountered by the Currowan Fire on 4th January 2020. Firefighter interviews mentioned that this burn split the fire, which was burning very intensely from the south, reducing the risk to the town of Bundanoon. The firefighters did not attend this area, being fully occupied with property protection, so it's effect was entirely passive. The shadow is very clear from the severity map (Figure 5.4). The second fire was the CCA Middle Creek LMZ fire, implemented in August 2015 and encountered by the Kangawalla fire on 10th November 2019. The confidence in this shadow was low (Figure 5.4) because fire severity was abating in the area anyway, and we have no corroboration from interviews.



HLAN - Brooks Plateau North SFAZ, Currowan Fire, Shadow, High confidence.

GLEN - Teatreel LMZ - Teatree Trl HR, Kangawalla Fire, Shadow, Medium

FIGURE 5.4. THE TWO HR BURNS WITH SOME EVIDENCE THAT THEY LEFT A SHADOW BEHIND THEM. THE ARROW INDICATES THE WIND DIRECTION AND THE LINES ARE THE APPROXIMATE SHADOW.

Stopping within patches

Of the 509 prescribed burns, 116 stopped the bushfire somewhere within the patch. This represents 22.8% effectiveness. Stopping effectiveness was related to the age of the burn, rising from 17% for burns before 2018 to 34% for 2018 burns and 50% for 2019 burns (Figure 5.5). Stopping was most likely in the northern region and least likely in the central. Stopping was more likely in larger burns in the SFAZ zone (26%) than the LMZ zone (19%). More than half of the stopping events (62) had low confidence and only 21 had high confidence.

The statistical analysis confirmed that the likelihood of stopping reduces with burn age and burn area, and that the centre region had lower likelihood (Table 5.3b).

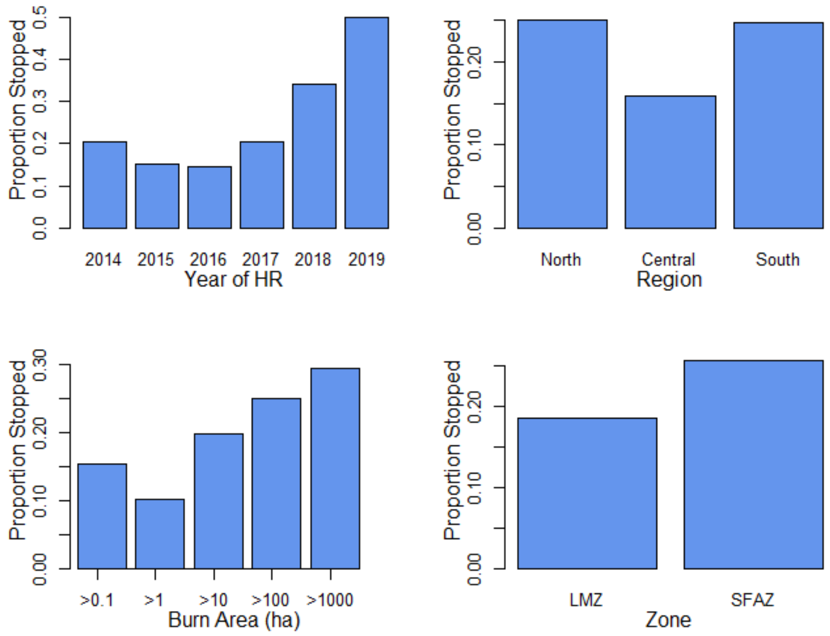


FIGURE 5.5. THE PROPORTION OF THE 509 BURNS THAT CAUSED THE BUSHFIRE TO STOP SOMEWHERE WITHIN THE PATCH, GROUPED BY YEAR OF BURN, REGION, BURN AREA AND ZONE.

Variable	Estimate	Std. Error	z value	Pr(>|z|)	
a) Stop at Boundary					
(Intercept)	-3.108	0.443	-7.015	0.000	***
Region: Centre	0.552	0.288	1.918	0.055	.
Log (Burn Area)	0.203	0.078	2.621	0.009	*
b) Stop inside burn					
(Intercept)	-0.932	0.385	-2.425	0.015	*
Region: Centre	-0.718	0.294	-2.447	0.014	*
Burn Age	-0.320	0.069	-4.656	0.000	***
Log (Burn Area)	0.135	0.060	2.225	0.026	*
c) Severity reduction					
(Intercept)	-2.301	0.770	-2.990	0.003	**
Region: Centre	-0.849	0.243	-3.492	0.000	***
Burn Age	0.335	0.234	1.427	0.154	
Log (Burn Area)	0.523	0.134	3.914	0.000	***
Burn Age * Log(Burn Area)	-0.103	0.041	-2.534	0.011	*

TABLE 5.3. STATISTICAL MODEL OF A) STOPPING AT THE BUSHFIRE BOUNDARY; B) BUSHFIRE STOPPING WITHIN THE BURN; AND C) SEVERITY REDUCTION AS A FUNCTION OF REGION, FIRE SIZE AND BURN AGE.

Some of these events could be cross-referenced to the interviews, including three cases from the Green Wattle fire in December 2019. The advantage was used to target firefighting elsewhere to stop the bushfire in other places nearby. The Green Wattle fire encountered the 2014 Dinner Creek burn in the Burragorong State Conservation Area on the 9th December 2019 (Figure 5.6). The burn caused a substantial reduction in bushfire behaviour and allowed firefighters to conduct a backburn and mop-up around houses. The 2019 Werrombi burn forms part of the eastern boundary of the Green Wattle fire, where it stopped on 14th December 2019. In our GIS analysis, we recorded with burn as not stopping the bushfire because the wind direction was from the east, blowing from the burn toward the bushfire (Figure 5.7). However, the firefighters reported that the burn did hold the bushfire and allowed them to redirect aircraft elsewhere. We used this intelligence to correct the GIS data. The Green Wattle fire was intense as it encountered the 2019 Rocky Waterholes burn on 21st December 2019, and it immediately reduced in intensity and stopped in some places, as confirmed by firefighter interviews (Figure 5.7).

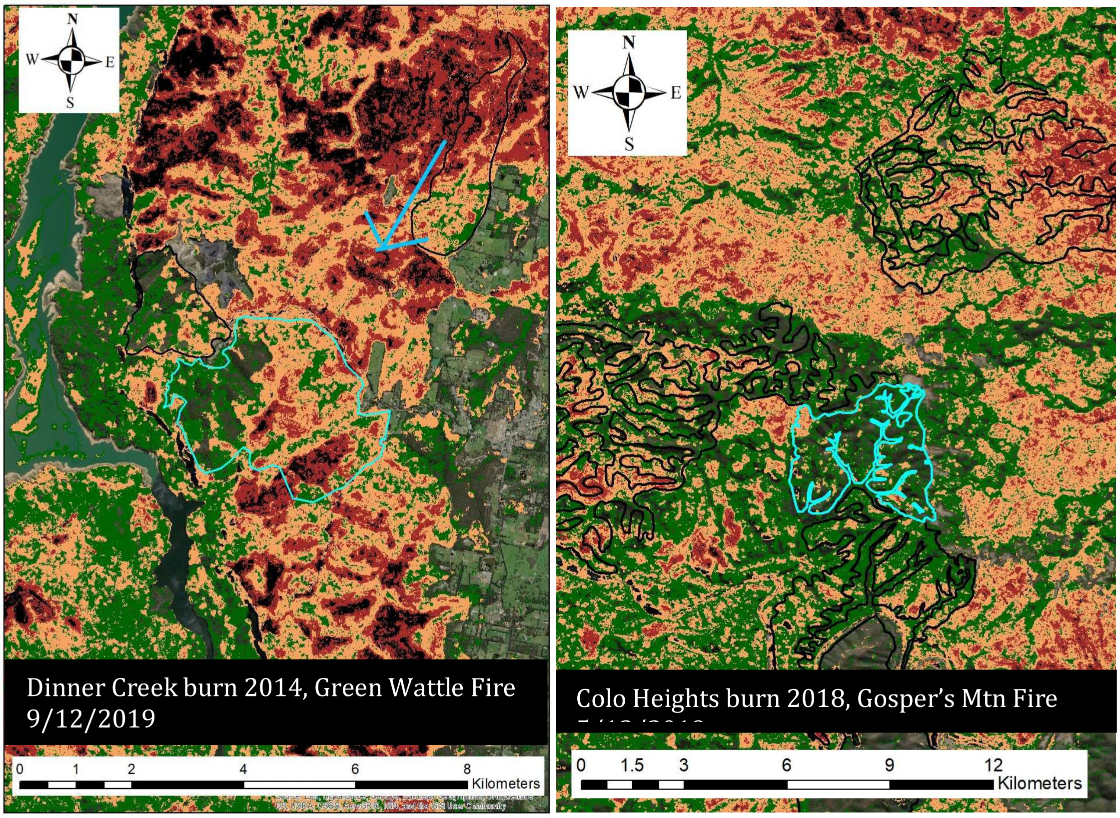


FIGURE 5.6. TWO EXAMPLES OF STOPPING WITHIN THE PATCH THAT WERE USED TO ADVANTAGE BY FIREFIGHTERS. THE ARROW INDICATES THE

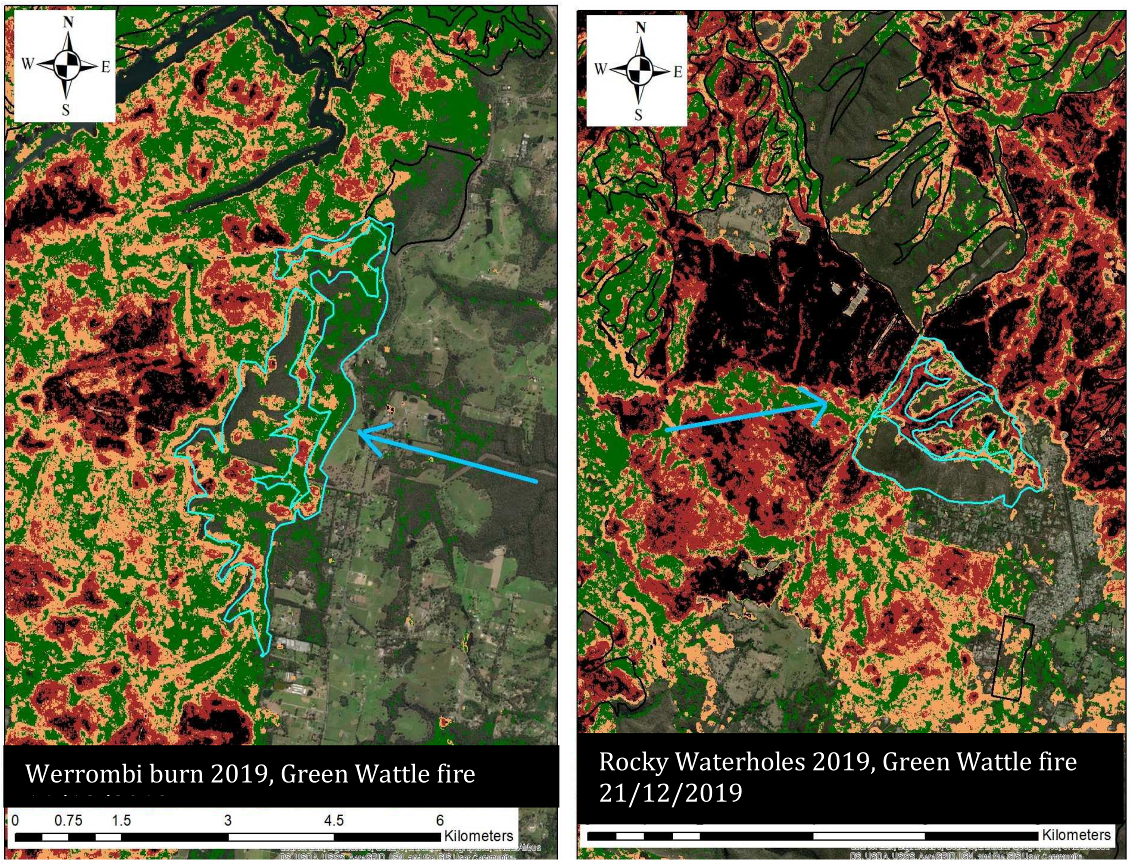


FIGURE 5.7. TWO MORE EXAMPLES OF STOPPING WITHIN THE PATCH THAT WERE USED TO ADVANTAGE BY FIREFIGHTERS.

Severity reduction

More burns showed a severity reduction than stopping, because stopping is a sub-group where the severity reduction is more substantial. Overall 42% of burns showed some severity reduction, and this rose from 34% for burns prior to 2018 to 66% for 2018 and 71% for 2019 (Figure 5.8). As with stopping, severity reduction was less common in the centre region than the others. Severity reduction was slightly more common in the LMZ zone than in the SFAZ zone (44% vs 39%). The statistical model for severity reduction was similar to that for stopping (Table 5.3c) but included an interaction between burn age and burn area suggesting that severity reduction in recent burns is much more likely in larger fires than small ones (Figure 5.9).

Some of these events were corroborated by the interviews. The May 2018 Rocky Creek burn in the western Wollemi National Park showed a substantial severity reduction. The Firefighter interview related that the Gospers Mtn Bushfire stopped for several days in the burn, even though it later burnt through when the fire weather deteriorated (Figure 5.10), and this enabled them to redeploy resources. The August 2018 Esk SFAZ burn reduced the severity of the Myall Creek Road bushfire so contributing substantially to their efforts to contain the northerly spread. We had marked that one as not showing severity reduction because there were many low severity patches around the burn.

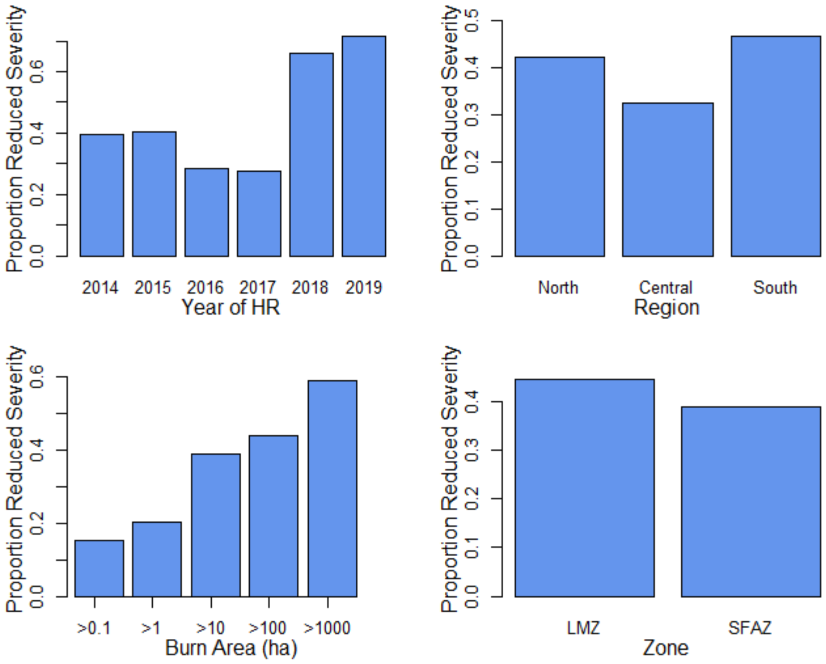


FIGURE 5.8. THE PROPORTION OF THE 509 BURNS THAT CAUSED A REDUCTION IN SEVERITY, GROUPED BY YEAR OF BURN, REGION, BURN AREA AND ZONE.

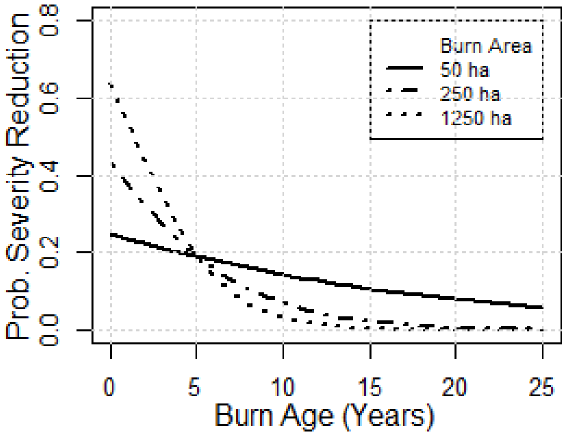


FIGURE 5.9. PREDICTIONS FROM THE STATISTICAL MODEL OF THE PROBABILITY OF BUSHFIRE SEVERITY REDUCTION SHOWING THE INTERACTION BETWEEN BURN AGE AND BURN AREA

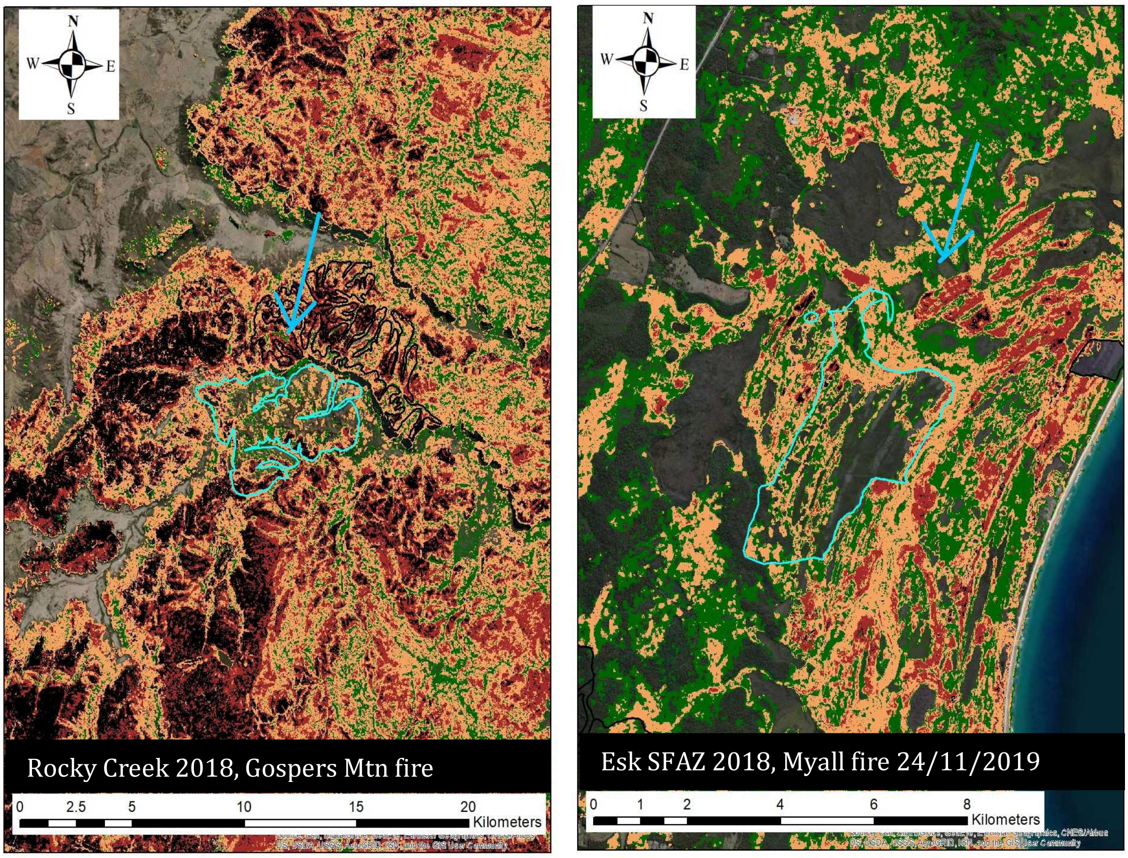


FIGURE 5.10. TWO MORE EXAMPLES OF SEVERITY REDUCTION WITHIN THE PATCH THAT WERE USED TO ADVANTAGE BY FIREFIGHTERS.

We examined examples of recent burns that did not reduce bushfire severity to try to understand the reasons. The best example involves a comparison of the Back Run Creek burn (March 2019) which did not influence the Currowan bushfire, and the Brooks Plateau (Feb. 2019), only 3 km away which was the one mentioned above as stopping the bushfire. The reason for the difference is that large parts of Brookes plateau burnt at high severity whereas most of Back Run Creek did not burn at all. This can be seen in the FESM severity map produced for the two burns (Figure 5.11). There were 20 cases around the state, where a 2019 burn did not appear to have any effect on the subsequent bushfire. Although we have not formally analysed them, about half of them appear as though there was probably little fuel reduction in the burn and the other half occurred in places where the bushfire was burning at low severity in the surrounding landscape anyway.

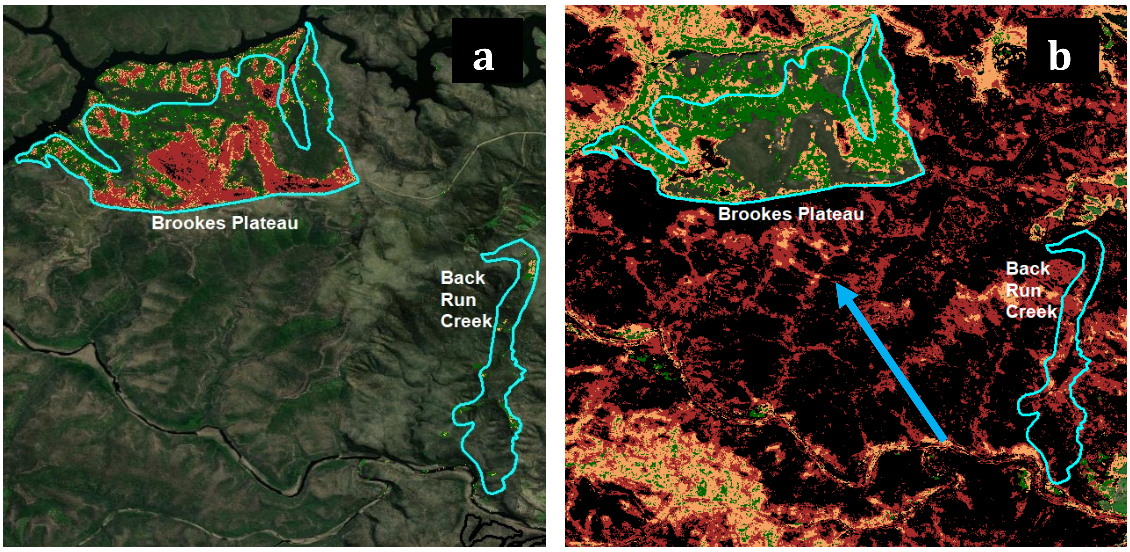


FIGURE 5.11. TWO BURNS IMPLEMENTED IN MORETON NATIONAL PARK IN FEB/MARCH 2019. MAP A) SHOWS THE FESM SEVERITY FOR THE PRESCRIBED BURNS AND MAP B) SHOWS THE FESM SEVERITY IN THE CURROWAN FIRE IN JANUARY 2020. IT SEEMS THAT THE SEVERITY OF THE PRESCRIBED BURN INFLUENCED THE SEVERITY OF THE SUBSEQUENT BUSHFIRE.

DISCUSSION/CONCLUSIONS

This analysis of the effects of prescribed burns on subsequent fire behaviour as can be determined from manual interpretation of GIS layers, is only one aspect of possible burn program evaluations, but nevertheless it generated results that are useful to managers.

1. Few burns actually encounter bushfire.

Even though the 2019/20 bushfires were unprecedented in area, only 30% of burns encountered the bushfires. Even accounting for the fact that a small proportion of the burns would have encountered bushfires in the years before the 2019/20 season, it has to be concluded that most burns were 'wasted'. This happens because managers cannot predict where bushfires will occur and have to hedge their bets.

2. 69% of burns no more than 2 years reduced bushfire severity.

Burns older than this were much less effective. It is likely that effectiveness was particularly low in 2019/20 because that year was so extraordinary in terms of drought, the size of the bushfires and the difficulty of suppression. For example, it is possible that the normal advantage of having low surface fuel was overcome during the bushfire because the live fuel in shrubs and tree canopies was so dry that the bushfires could spread with little surface fuel. Previous fire severity studies typically find an effect for 5–7 years after a prescribed burn (Bradstock *et al.* 2010; Price and Bradstock 2012; Storey *et al.* 2016). Our finding agrees very well with other studies of severity reduction in the 2019/20 season (Hislop *et al.* 2020; Pedroza *et al.* 2020). For example our manual interpretation of severity reduction is very similar to (Hislop *et al.* 2020) who found 48% of burns reduced severity, rising to 66% for one year old burns: we found 42% overall and 71% for one year old burns. The difference between finding for the 2019/20 fires and previous studies reinforces the conclusion that prescribed burns were less effective in drought conditions than in normal years.

3. 42% of these recent burns also caused unburnt patches somewhere in the patch.

The APR interviews indicated that this is often associated with a firefighting advantage such as delaying the fire to allow containment lines to be strengthened or resources to be sent to higher priority areas. This benefit is essentially overlooked in standard analyses of fire severity.

4. 13% of the burns were aligned with the bushfire boundary.

For this phenomenon there was no effect of burn age, 37% had low confidence because the wind was blowing away the burn toward the bushfire, and 62% of them showed no unburnt patches within the burn. These three facts suggest that many of these events are coincidental with other effects that contributed either partly or wholly to the stopping event. A complete coincidence would occur where the burn was aligned with a road or river which actually stopped the bushfire. A partial coincidence would be where firefighters suppressed the bushfire at the line where the burn met a road. This partial coincidence was suggested for many of the fire stopping events in Price and Bradstock's (2010) study in the Sydney region. Whatever, the reason, we can conclude that burns stopping bushfires unassisted is a rare phenomenon.

5. Leaving an unburnt shadow behind a burn is a very rare phenomenon.

There were only two such events among 509 burns, and one of these was uncertain. It seems that bushfires almost always burn through or else around burns.

6. Effectiveness at stopping and reducing severity also increases with burn size.

This may not actually mean much in terms of the usefulness of larger burns because larger fires would show higher effectiveness simply because there is more chance of a phenomenon occurring as the patch size gets bigger (even if it were random).

7. There are slight differences in effectiveness among regions and management zones.

The reasons for these differences are not clear.

8. Positive effects of prescribed burns on bushfire may not be detected in GIS.

There were five cases identified in the APR Interviews where the burn gave an advantage to firefighters which could not have been known from the GIS analysis alone. This highlights the need to combine GIS and interview data in the fire-meets-fire dataset.

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DISCUSSION/RECOMMENDATIONS

The objective of this project was stated in the Research Services Agreement as: "to develop a novel dataset that will capture information about individual bushfire-meets-prescribed burn events. The initial focus will be on those interactions that occurred during the 2019/20 fire season." In other words, the project was to design a database that will allow evaluation of prescribed burns from planning stages to ultimate outcomes, and start using the data for some cases. In this report, we begin by outlining this dataset and its sources of information, though we have not populated it. Instead, we list potential evaluations that could be done with and conduct two evaluations with components of the data.

The core of the proposed fire-meets-fire dataset is matched reporting from the Burn Plan (before) and Burn Report (on completion), especially area, fuel, moisture and weather variables. Some of this is not routinely reported in the current Elements System (for example 21% of burns had no actual area burnt recorded and most burns were missing fuel information). The dataset should also ingest information from fire severity mapping (which is now routine) and smoke impact. If the burn meets a bushfire a new range of information is available and should be ingested, including the severity of the bushfire within the burn. The advantage that the burn gave to firefighters is hard to gauge simply from fire severity, so additional information is needed, most importantly from firefighter interviews, but also by more detailed GIS examination of bushfire behavior.

There are many evaluations that could be done with this dataset, from simple metrics such as percent of planned area actually burnt, to refinement of weather prescriptions for burns to whole-of-program evaluations applied to all burns such as the severity analysis presented here.

Sections 3 and 4 are examples of whole of program evaluations. Section 4 is an analysis of severity reduction in the 2019/20 bushfires relating the occurrence of high severity fire in ~100,000 points to the fire history at those points, and controlling for vegetation, weather and topography. This found that in dry sclerophyll, recent burning (up to ~5 years) reduced the probability of high severity fire and even more so if that previous burn was at low severity.

Section 4 uses visual interpretation of the 2019/20 bushfire severity and progression mapping to attribute each previous prescribed burn with its effect on the bushfire. This ranged from stopping the bushfire altogether (having a common boundary), to simple severity reduction (was the bushfire severity reduced in the burn?). We found that 30% of burns from 2014 were encountered by the bushfires. Of these 509 burns, 13% of them were aligned with the final fire boundary, 42% of recent burns (1 or 2 years old) caused some unburnt patches within the burn, and 68% caused a severity reduction. Burns older than this had much less effect, and we found two cases where a burn left an unburnt shadow behind it (meaning shadows are very rare events). We were able to cross-reference our interpretation for 14 burns to interviews from another pilot project. This revealed broad agreement, but also highlighted several cases where a burn gave firefighters an advantage that could not be found in the GIS. Three of these were cases where the bushfire slowed down (sometimes for several days), allowing firefighters time to prepare. There were two cases where burns outside of the burn perimeter effectively reduced spotting activity.

The project demonstrates what can be done to evaluate prescribed burning programs and that a wide range of data is required to do this thoroughly. The 2019/20 bushfire season was extraordinary in many ways. Our analysis suggests that one of these ways was that prescribed burns only reduced fire behavior if they were one or two years ago. Analyses of previous seasons generally find a longer lasting effect. Even so, there were many instances where prescribed burns helped firefighters, including in ways that are not obvious in GIS analyses.

We recommend:

1. That DPIE implement the fire-meets-fire database that we have outlined.
2. Strengthens current reporting that at present misses some important information (most notably fuel amount and moisture content measurements).
3. Develops work-flows to routinely ingest other information including FESM severity mapping, weather and smoke information.
4. Conducts interviews like those in the APR Interview project to document the advantage gained by each burn. These may be after significant bushfires or at the end of a season. They should be summarised into the fire-meets-fire database and used to cross-reference other evaluations.
5. Evaluations such as those in sections 3 and 4 (FESM severity, GIS-based fire behavior), should be carried out each year or after major seasons.
6. Continue to support research projects to provide in-depth analyses of the data (such as exploration of burn windows, escapes, and the factors