CSIRO PUBLISHING

International Journal of Wildland Fire **2021**, *30*, 90–111
https://doi.org/10.1071/WF19105

Spatial databases and techniques to assist with prescribed fire management in the south-east Queensland bioregion

Sanjeev Kumar Srivastava[A,B,F], *Tom Lewis*[B,C], *Linda Behrendorff*[D] *and Stuart Phinn*[E]

[A]Genecology Research Centre, University of the Sunshine Coast, Sunshine Coast, Qld 4556, Australia.
[B]School of Science and Engineering, University of the Sunshine Coast, Sunshine Coast, Qld 4556, Australia.
[C]Department of Agriculture and Fisheries, Sippy Downs, Qld 4556, Australia.
[D]School of Agriculture and Food Science, The University of Queensland, Gatton, Qld 4343, Australia.
[E]School of Earth and Environmental Sciences, The University of Queensland, St Lucia, Qld 4072, Australia.
[F]Corresponding author. Email: SSRIVast@usc.edu.au

Abstract. This paper identifies key fire history and fire-related spatial databases that can be utilised for effective planning and assessment of prescribed burns in south-eastern Queensland. To ensure that appropriate fire regimes are maintained for specific management objectives (e.g. biodiversity conservation or risk management), and to assist fire managers with planning prescribed fire and post-fire assessments, we describe, using case studies and existing tools, the application of remote sensing data and derived burned area products together with field data to potentially: (1) improve mapping of fire-prone areas; (2) improve the accuracy of mapping burned areas; (3) monitor temporal changes in fuel structure; and (4) map post-fire severity. This study utilised data collected from aerial and satellite-based multispectral, microwave and laser (LiDAR) sensors. There are several spatial databases and analytical methods available that are not currently used by fire management agencies in this region. For example, the methods to estimate fuel, such as LiDAR, are underutilised and unburned patches within a burned area are not routinely mapped. Better use of spatial datasets could lead to an improved understanding of variables such as fuel status, resulting in more efficient use of fire management resources.

Keywords: burned-area mapping, fire regimes, fuel mapping, prescribed fire management, regional, remote sensing of fire, southeast Queensland.

Received 11 July 2019, accepted 4 October 2020, published online 29 October 2020

Introduction

Australia is a continent of remarkable biological diversity, predominantly shaped by fire regime, diversity of climates and geomorphology (Tran and Wild 2000). Fire is a ubiquitous natural disturbance agent in most Australian ecosystems (Gill 1975; Moritz *et al.* 2014) and can have both positive and negative consequences for ecological processes, society, economics and global climate (Turner *et al.* 2008). In Australia, deliberate and purposeful burning has most likely been performed over the last 65 000 years of human occupation (Clarkson *et al.* 2017). Currently, prescribed burning is an essential wildfire mitigation strategy in the Australian landscape, not only for maintaining ecological health but also for reducing risk to communities (Australasian Fire and Emergency Service Authorities Council (AFAC) 2017*a*). An improved understanding of the locations of previous fires (e.g. fire regime) and likely occurrence of future fires could help predict the consequences and effectiveness of prescribed fire. In this study, we use the south-east Queensland region of Australia as a case study to review existing geospatial resources that can potentially enhance fire management planning.

Prescribed burning across Australia is governed by policies that are implemented at a national level, for example, by the National Bushfire Management Policy Statement, and through organisations such as AFAC and the Forest Fire Management Group (FFMG). However, the individual state governments provide guidelines for prescribed burning that are followed by agencies responsible for fire management. There are four hierarchical phases of planning and implementation, where prescribed burn implementation is governed by operational planning pre-arranged over a year. Operational planning is governed by program planning (1–5 years) and strategic planning (>5 years). The AFAC objective, monitoring, evaluation and reporting framework contains many high-level principles; there are 20 principles for strategic and program planning phases, and another 17 principles for operational planning and burn implementation phases (AFAC 2017*a*).

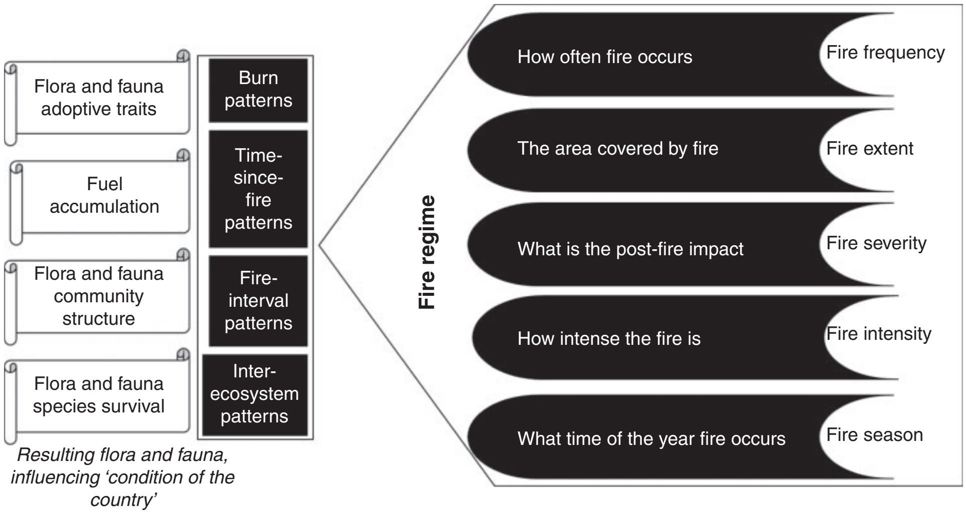


Fig. 1. Components of the fire regime modified from Gill (1998).

In Queensland, for emergency fire situations and protection of persons, property and the environment, the Queensland Fire and Emergency Services (QFES) is the primary provider in the area of the present study. QFES works together with the Rural Fire Service (RFS), State Emergency Service (SES), Queensland Police, Queensland Ambulance Services and the Bureau of Meteorology and other state government agencies. Management of fire on state land is primarily carried out by the Queensland Parks and Wildlife Service and Partnerships (QPWS&P), which is part of the Department of Environment and Science, together with the RFS, QFES and Queensland Department of Agriculture and Fisheries (DAF). Local government (councils) is also responsible for sustainable fire management in the south-east Queensland bioregion. As the main tenure holder in south-east Queensland, QPWS&P must consider not only the sustainable management of endemic flora, fauna and healthy ecosystems but also the protection of life and property (Queensland Government 2018). Thus, fire management requirements vary depending on the institutional objectives for a given location. In all situations, prescribed burning plays a key role.

The principles governing prescribed burning emphasise that the objectives, as well as monitoring and evaluation, should be integrated into the fire management system applied by organisations undertaking prescribed burning activities. Another principle of prescribed burning requires using measurable objectives so that the outcome can be quantified in terms of prevention of property loss, ecological damage and ecological benefits. To properly monitor and evaluate a prescribed burn, it is important to clearly define the objectives of the burn. If the prescribed burn is performed with multiple objectives, then all individual objectives should be measurable (AFAC 2017*b*) and the adaptive management cycle following the Object, Orient, Decide and Act (OODA) loop can be used to assess if the objectives have been met. This can be achieved through post-burn data collection of relevant environmental and ecological parameters using a range of geospatial methods at predetermined times (e.g. immediately after the burn and at monthly or yearly intervals). The complexity of monitoring and evaluation techniques will depend on the scale at which prescribed burning is applied. All fire management, regardless of scale, relies on accurate burnt area mapping, but effective fire management at regional or local scales needs precise mapping, which may rely on high-resolution data sources in combination with field surveys.

Information resources required for implementing an effective prescribed burn

Fire regime

The fire regime is defined as the characteristics of fire over a period (e.g. 20 years) encompassing frequency, intensity, severity, between-fire interval, extent, seasonality and type of fire (Fig. 1) (Gill 1998; Krebs *et al.* 2010; Parker *et al.* 2015). Fire regime information is useful for all the phases of prescribed burn planning, for example, to prioritise burn scheduling after risk assessment. The various data sources available for characterising different components of the fire regime and the subsequent patterns in vegetation for the south-east Queensland bioregion include detailed descriptions of vegetation types, their fuel characteristics, detailed information about burn history, topographic information and climatic data.

It is important to have information about vegetation and fuel types, the historic fire regime and long-term weather conditions for linking burn implementation with strategic planning. At all geographic scales, vegetation type and structure are the key parameters associated with fuel characteristics that influence fire frequency and intensity (Mutlu *et al.* 2008; Srivastava *et al.* 2013). As such, one of the first steps for landscape fire management relies on effective vegetation mapping (Keane *et al.* 2001) at an appropriate scale. Vegetation in the south-east Queensland bioregion varies in flammability, ranging from rainforests with lower flammability to higher-flammability eucalypt forests, woodlands and shrubby heathlands (Gill and Zylstra 2005). Most vegetation types in the south-east Queensland bioregion are tolerant of fire and can recover rapidly after fire through various mechanisms (e.g. resprouting, seed regeneration). However, the prevailing fire regime, in particular, fire frequency and intensity, has strong influences on vegetation structure and composition (Russell-Smith *et al.* 2003). Accurate mapping of the fire regime together with on-ground biodiversity monitoring allow assessment of whether prescribed burning goals for ecological purposes are being achieved, for example, by assessing whether the fire frequency at a given location is appropriate based on current recommendations for the respective ecosystems. Detailed maps of fire history for a given location (e.g. a national park) provide key tools for determining where prescribed burning should be targeted and complement existing guidelines (e.g. planned burn guidelines) and on-ground assessments (Queensland Government 2018).

Using contemporary spatial technologies, the components of the fire regime can be mapped using multitemporal remote sensing data and geographic information systems (GIS) datasets available for the area. Previous studies have recommended the integration of field datasets, fire history maps, remote sensing data and biophysical datasets to map fire regime as well as fuel types and distribution (Keane *et al.* 2001; Rollins *et al.* 2004). Although the data sources and technology exist for the construction of long-term fire history archives, this type of database is rarely used by fire management agencies in strategic planning. Fire regime mapping at regional and local scales rarely incorporates all aspects of the regime (e.g. patchiness and severity) (Srivastava *et al.* 2013; Russell-Smith *et al.* 2017). This may be partly due to a lack of knowledge regarding existing datasets that can be used for mapping the fire regime and also due to underappreciation of the ecological as well as the operational significance of patchiness and severity.

Prescribed fire management

Fire management in a given ecosystem generally aims to avoid:

- High fire intensity (with exceptions for certain ecosystems where regeneration of some plant species is promoted by high-intensity fire, or where the high-intensity fire is initially used to control weed populations),
- Complete and homogeneous consumption of fuels over a large area (with exceptions for protection zones where the aims are to reduce fuel loads),
- Intervals that are either too short or too long for the ecosystem.

Patch mosaic burning and staged burning of smaller blocks are strategies used to minimise the above factors, where small areas with accumulated fuel are burned at a time interval defined by species requirements (Parr and Andersen 2006). Under ideal conditions, such prescribed burning across the landscape could create a heterogeneous distribution of fuel and habitats (e.g. differing vegetation structure). Traditional custodian burning practices generally aim to achieve this (QPWS&P 2011). Most often, fires burn heterogeneously across landscapes, with unburned and lightly burned patches interspersed among severely burned patches. The heterogeneous distribution of fuel, often referred to as the invisible mosaic, can be achieved by performing prescribed burning on areas identified with steady-state fuel (Fig. 2).

To achieve the desired number of prescribed burns across the landscape, government agencies face challenges such as resources constraints (e.g. staff and contract capacity, training requirements and fire-appropriate vehicles), logistical constraints (e.g. narrow windows of time in which burns can be safely conducted), political and community pressures (e.g. smoke from prescribed burns influencing human health) and competing priorities (e.g. managing public visitations to natural areas).

Planning and measuring the effectiveness of a prescribed burn

An effective prescribed burn must be executed safely under controlled conditions and accomplishes the prescribed treatment as well as land management objectives (Fischer 1978). For continuous improvement of prescribed fire management, the evaluation cycle should be followed, including aspects such as aims, planning, execution and evaluation. The spatial databases presented in the present study can feed into the planning–evaluation cycle to assist in the process and encourage feedback, reporting and improvement for subsequent fires (Fig. 3).

The practical application of prescribed burning in Australia is increasingly administratively and logistically complex, controversial and climatically challenging, especially in densely settled regions with high fire risk due to adjacent native vegetation. Annually, many fire management agencies in Australia aim to perform prescribed burning over ~5% of the total area of flammable ecosystems.

Fuels are defined as the live and dead combustible biomass that can potentially contribute to the spread and intensity of fire (Rollins *et al.* 2004). A key aim of prescribed burning is fuel reduction and modification (Gill 2008). Such an aim can be measured in the following ways (Moore and Shields 1996; Gill 2008):

1. Reducing total fuel weight to lower fire intensity and rate of spread of subsequent fires
2. Reducing fuel bed height to achieve a lower flame height of subsequent fires
3. Reducing vertical fuel connectivity to prevent the fire from spreading into tree canopies during subsequent fires
4. Reducing the distribution of continuous fuels over a large area to limit the rate of spread of subsequent fires
5. Removing flammable materials such as fibrous bark to minimise chances of subsequent spot fires.

In this paper, we discuss the application of available datasets and sources that could assist fire management in different flammable vegetation types in the south-east Queensland bioregion using four case studies. The degree to which spatial datasets are utilised for fire management in this region is discussed. The combination of spatial datasets presented may not only help in setting prescribed burning targets but could also play a useful role in measuring the effectiveness of prescribed burns.

QPWS&P as an example

The QPWS&P performs prescribed burning in the study area with support from a local Fire Management Thematic Strategy underpinned by the Planned Burn Guidelines (Queensland Government 2018). As per the requirements of the Nature Conservation Act 1992, QPWS&P must meet custodial obligations in terms of mitigating risks to life and property while also managing the ecological components that safeguard the estate's key values. The Thematic Strategy is reviewed before

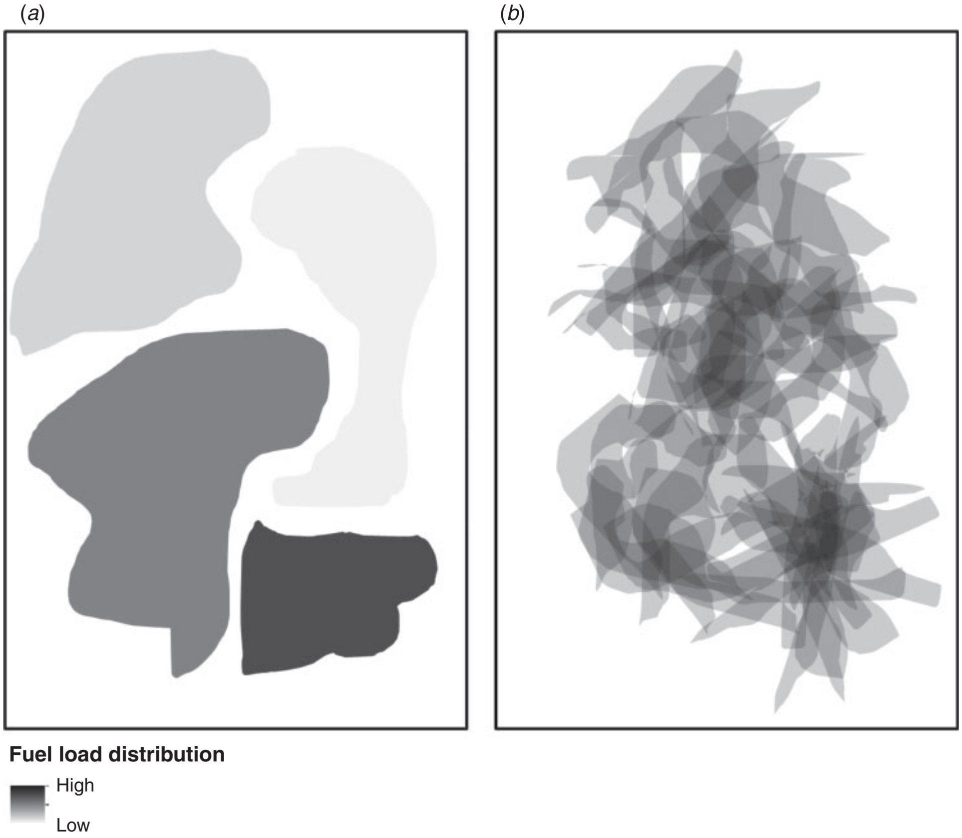


Fig. 2. A theoretical model indicating two contrasting distributions of fuel loads in an ecosystem: (*a*) likely fuel loads based on time since the last fire in different burned patches; (*b*) an invisible mosaic of fuel based on patterns of historic burn patchiness.

commencing a burn proposal to ensure all ecological issues are considered. This includes relevant legislation, fire history, vegetation types, zoning, cultural heritage values and rare and threatened species of the proposed burn and surrounding area. In certain areas, current QPWS&P management aims to incorporate traditional burning methods and to strategically increase the capacity of contracting and partnering with the Traditional Custodians (QPWS&P 2011, 2019). A burn proposal incorporates measurable objectives (e.g. protection, mitigation, cultural or land management), predicted fire behaviour, tactics and weather conditions required to meet the burn parameters based on the burn objectives. The Planned Burn Guidelines promote observations of the environment (e.g. health or decline of different vegetation layers) to determine when an area is 'ready' for a burn and to use these cues to keep vegetation ecosystems 'healthy' before it becomes too difficult to implement a prescribed burn (QPWS 2013). The guidelines are also used to predict fire behaviour and the likelihood that burn plan objectives can be achieved (Table 1).

QPWS&P burn proposals are documented in a spatially enabled web-based IT system, purpose-built for the department. This system is called FLAME and allows any point of query within the estate to be interrogated at a point in time, allowing a comprehensive oversight into fire history (including fire intensity, burn parameters, tactics, situation reporting, costings, outcomes) as well as future planning. In the study area, a stringent approval process is required to support the burn proposals and incorporate them into a burn plan register as a part of the QPWS&P FLAME system. Proposals produced by operational staff are put through a referral committee made up of highly experienced staff local to the estate, Traditional Custodians, experienced fire practitioners, technicians, managers and ecologists to discuss the objectives and tactics, including prescribed burn implementation within long unburned areas and risky residential zone areas. This committee is similarly replicated in other states and territories in terms of representation and to review and recommend on-ground programs. Approval from management on the day of the burn is also required before light-up commences. The current QPWS&P practices include perimeter mapping after a prescribed burn, and this information is used for estimating time-since-burn to guide future prescribed burns.

Availability of datasets

The Australian and Queensland governments follow an open-data policy enabling anyone to access public data published by federal, state and local government agencies through their data portals (Tanner 2010; Burton *et al.* 2012; Srivastava 2015; Queensland Government 2020). These datasets are highly useful for land managers to plan burn practices in flammable ecosystems (Table 2).

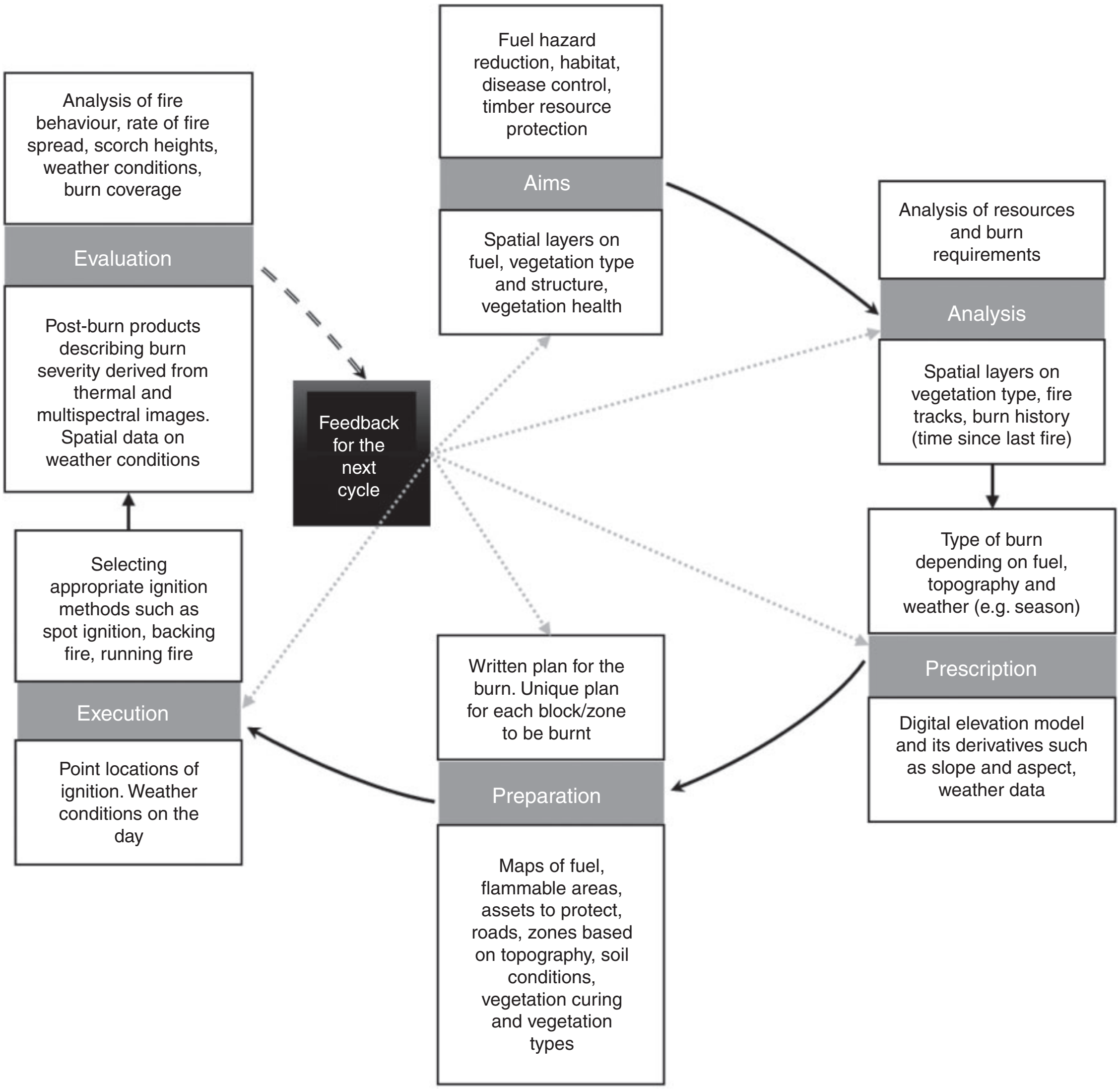


Fig. 3. The evaluation cycle for prescribed burns. For each step of the cycle (Aims, Analysis, Prescription, Preparation, Execution and Evaluation), typical considerations are given (in the box above each step) and the associated spatial databases listed (box below each step).

Vegetation data

Fire management approaches vary depending on vegetation types and it is recommended that strategic plans for prescribed burning should consider vegetation types (AFAC 2017*a*, 2017*b*). Vegetation–fire associations can be derived from the regional ecosystem mapping in Queensland (Appendix 1), which describes the vegetation structure and composition associated with particular combinations of geology, soil and landscape position in different regions (Neldner *et al.* 2017; Queensland Herbarium 2018).

Fuel load and accumulation

Fuel accumulation is a key consideration for defining the scale of planning prescribed burning (planning period and geographic extent), for analysing landscape fire movement and for predicting fire behaviour (AFAC 2017*a*, 2017*b*). The main objective of hazard reduction burning is to reduce fuel levels during mild weather conditions and appropriate soil moisture, thereby reducing the intensity and impact of any subsequent wildfire burning under adverse weather conditions. Accordingly, the amount of fuel reduced by a fire, and its recovery to pre-fire levels, is of particular interest to land managers (Tolhurst and Flinn 1992). Several approaches and models provide an estimate of fuel accumulation according to vegetation types and structure (Walker 1981; Birk and Bridges 1989; Keane *et al.* 2001; Bridges 2004; Gilroy and Tran 2006; Yebra *et al.* 2015).

Remote sensing data

Remote sensing data and derived data products are useful data sources for fire management planning and implementation. Currently, there is a wide range of remote sensing platforms with

Table 1. Summary of current practices used by key fire management agencies in south-east Queensland bioregion

This includes strategic, program, operational planning and monitoring and evaluation used in fire management systems for the key fire management agencies in the bioregion. QPWS&P is the main agency responsible for prescribed burning on Crown land in the bioregion, whereas QFES and the RFS respond to emergency fire situations, with assistance from other agencies, but also undertake prescribed burning for wildfire mitigation

Fire management and planning	Current practices
Strategic planning	QFES and RFS focus on bushfire prevention and preparedness (consistent with the State Disaster Management Plan) (QFES 2019). Prescribed burning through Operation Cool Burn Fire Management Thematic Strategy QPWS&P applies different strategies to different zones (e.g. protection, wildfire mitigation, sustainable production zones) based on objectives for that zone. Particular consideration is given for urban–rural interface areas and protection burning
Program planning	QFES and RFS have multiple strategies considered at a local level in collaboration with land managers. For example, adopting the principles of Aboriginal patch-mosaic burning is an important potential strategy to improve fire management and biodiversity outcomes. Bushfire-prone area mapping is conducted to assist in program planning QPWS&P considers fire management priorities, burn objectives and uses Bioregional Planned Burn Guidelines. Burn proposals are developed and objectives are listed in the burn proposal. Recognises that adopting the principles of Aboriginal patch-mosaic burning is an important potential strategy to improve fire management and biodiversity outcomes QPWS&P conducts staged burning practices with mosaic outcomes for broadacre burns
Operational planning	QFES and RFS coordinate land managers to mitigate bushfire risk. Operational Cool Burn plan aimed at mitigating wildfire risk. Support provided to RFS (volunteers) QPWS&P uses planned burn guidelines 'How to assess if your burn is ready to go'. Burn tactics are considered appropriate to meet objectives. Fuel load and connectivity assessments and 'Overall fuel hazard assessment' (Hines *et al.* 2010) may be conducted before a burn
Monitoring and evaluation of prescribed burn	QFES and RFS fire history data collated from a range of sources Post-fire recovery assessments outsourced in some cases (e.g. Bushfire Rapid Risk Assessment Team) QPWS&P assesses if objectives of the burn proposal have been met. It conducts perimeter mapping on a routine basis and maintains observations of the land where burning is carried out (e.g. using photographic observation points)

a range of scanner types continuously collecting information across visible, infrared and microwave spectra. Most remote sensing sensors have visible and near-infrared sensors; for fire mapping purposes, shortwave infrared (this spectrum is well recognised for distinguishing burned areas) and thermal infrared spectra (not only useful for active fire but also post-burn because the temperature of burned areas remains 5–6°C higher than surrounding areas) provide additional information (García and Caselles 1991; Miller *et al.* 2009). Key remote sensing satellites for burned area mapping are listed in Appendix 2.

Burned area products

From the 1980s onwards, global burned area products derived from remote sensing data have kept improving in their temporal and spatial resolution (Mouillot *et al.* 2014). Key global burn products are listed in Appendix 3 and several studies have evaluated and compared these products (Huesca *et al.* 2013; Humber *et al.* 2018).

Methods

Study area

The south-east Queensland bioregion was selected as a case study region to investigate the availability of spatial databases and their utility to guide prescribed fire management (Fig. 4). The boundary of this region was based on the 'bioregion' classification used for regional ecosystem mapping in Queensland. Four case studies are presented to illustrate the practical use of spatial datasets within the study area. This study area was selected because (1) prescribed fire is a commonly used by government agencies in this region; (2) the region contains a diverse range of vegetation types, suitable for case studies; and (3) spatial data and data for field validation were available within the region (Eliott *et al.* 2020). Details on fire management in south-east Queensland are provided in Eliott *et al.* (2020).

Datasets and spatial analysis

Fraser Island (K'gari) and surrounding areas, Bauple State Forest and Beerwah scientific area were selected as case study sites to demonstrate the availability of spatial databases and their utility to guide prescribed burning practices by fire managers. Where possible, case studies utilised existing long-term fire experiments in the region (Lewis and Debuse 2012; Lewis *et al.* 2012), where the detailed fire history is available for at least 40 years, providing useful insights for validating remote datasets with archived field information. The datasets used in the present study are listed in Table 2. Burned area products (MCD45A1, MCD64A1 L3JRC and MERIS) were downloaded from the respective web portals for the study area. Additionally, the burned area product available for Queensland for the year 2016 was downloaded from the QSpatial website (QSpatial 2018).

Case study 1: Mapping fire-prone vegetation and fuels

Mapping fire-prone areas is important for predicting fire behaviour and risk. Although such mapping is routinely conducted by agencies such as QFES, it is not frequently used for

Table 2. Datasets, their sources and spatial analyses performed for this study.
Given the extent of the study area, the universal transverse Mercator coordinate system for zone 56S was used with the GDA1994 datum

Datasets	Data sources	Spatial analyses
Optical remote sensing data	The following datasets were used for this study: (1) For Case studies 2 and 4, Sentinel 2 data corresponding to different scenes were acquired on: 19 July 2018, 18 August 2018, 24 June 2017, 29 July 2017 (2) For Case studies 2 and 4, Landsat 8 data corresponding to different scenes were acquired on: 4 October 2013, 23 December 2013, 19 August 2017, and 15 May 2017 for Case study 1 (3) For Case study 3, Landsat 5 data corresponding to different scenes were acquired on: 22 October 2008, 23 November 2008, 27 July 2011 and 13 September 2011 (4) For Case study 3, multispectral digital aerial data were collected on 31 October 2008 at 0.2-m resolution and in red, green, blue and near-infrared spectrum. The analysis-ready rectified datasets were provided by the Sunshine Coast Council in digital multispectral format	All the optical remote sensing data products used in this study were derived after converting digital numbers to the top of the atmosphere reflectance values using *ENVI 5.5* software. (1) Normalised difference vegetation index (NDVI) was calculated for the Case study 3 multispectral digital aerial data using the following equation: $\mathrm{NDVIi} = \frac{\mathrm{NIRi-Ri}}{\mathrm{NIRi+Ri}}$ where NIRi is the near-infrared reflectance for pixel i and Ri is the red reflectance for pixel i. (2) Normalised burn ratio (NBR) was calculated for Case studies 2, 3 and 4 from pre and post-fire Landsat 5, Landsat 8 and Sentinel 2 data using the following equation: $\mathrm{NBRi} = \frac{\mathrm{NIRi-SWIRi}}{\mathrm{NIRi+SWIRi}}$ where NIRi is the near-infrared reflectance for pixel i and SWIRi is the shortwave infrared reflectance for pixel i. For Sentinel 2 data, the SWIR spectral band was resampled to 10 m (3) Differenced NBR (dNBR) was calculated by subtracting post-burn NBR from pre-burn NBR using the following equation: $\mathrm{dNBR} = \mathrm{NBR}_{\mathrm{preburn}} - \mathrm{NBR}_{\mathrm{postburn}}$ (4) For Case study 1, the thermal Landsat 8 datasets were calibrated to at-surface brightness temperature using calibration constants available with Landsat 8 metadata (in Kelvin).The pre and post land surface temperature (LST) data were differenced to calculate dLST using the following equation: $\mathrm{dLST} = \mathrm{LST}_{\mathrm{preburn}} - \mathrm{LST}_{\mathrm{postburn}}$
Radar data	For Case study 2, Sentinel 1 C-band radar Level 1 Ground Range Detected (GRD) products derived from Single Look Complex (SLC) datasets were downloaded from Sentinel Scientific Data Hub, which were acquired on 25 June 2017 and 31 July 2017. These datasets are collected in two polarisation modes: horizontal–horizontal (HH) and horizontal–vertical (HV)	All the radar remote sensing data used in this study were processed in *Sentinels Application Platform (SNAP) 6.0* software. The following steps were followed before analysing radar data: (1) Thermal noise removal (2) Radiometric calibration to convert raw digital numbers of VV and VH polarisations into backscattering coefficient (3) Filtering speckles (4) Terrain correction using SRTM 1-s digital elevation model using Range Doppler Correction (5) Thereafter, the normalised difference radar backscatter burn ratio (NDRBR) was calculated for VV and VH polarisation backscatter data separately using pre- and post-burn data. The following equations were used: $\mathrm{NDRBBvv} = \frac{\mathrm{VVpre\ fire-VVpost\ fire}}{\mathrm{VVpre\ fire+VVpost\ fire}}$ $\mathrm{NDRBBvh} = \frac{\mathrm{VHpre\ fire-VHpost\ fire}}{\mathrm{VHpre\ fire+VHpost\ fire}}$ The normalised differences between VV and VH polarised data were added to identify burned areas (Fig. 8) $\mathrm{NDRBBvvvh} = \mathrm{NDRBBvv} + \mathrm{NDRBBvh}$
LiDAR data	For Case study 3, LiDAR datasets were obtained for 2014 and 2018 from the Sunshine Coast Council for the Beerwah scientific area	Full-waveform aerial laser scan (referred as LiDAR) datasets were obtained from various sources and were preprocessed to merge tile covering study area and subsequently clipping them for the area of interest using *ArcGIS Pro* and *Laszip* software packages Digital surface model (DSM), digital elevation model (DEM) and Digital Lower Vegetation Model (DLVM) were derived for both the multitemporal LiDAR data to calculate Digital Canopy Model (DCM) and Lower Vegetation (LV) using the following equations: $\mathrm{DCM}_{\mathrm{y}} = \mathrm{DSM}_{\mathrm{y}} - \mathrm{DEM}_{\mathrm{y}}$ $\mathrm{LV}_{\mathrm{y}} = \mathrm{DLVM}_{\mathrm{y}} - \mathrm{DEM}_{\mathrm{y}}$ where y is the year of Lidar data collection.The change in vegetation was calculated using the following equations: $\mathrm{dDCM} = \mathrm{DCM}_{2018} - \mathrm{DCM}_{2014}$ $\mathrm{dLV} = \mathrm{LV}_{2018} - \mathrm{LV}_{2014}$
Field data	For Case study 4, all the field data used in this study were collected using Trimble GeoExplorer 6000 differential GNSS	The acquired positions were differentially corrected after collection using Geoscience Australia's nearest located Continuously Operating Reference Stations (CORS). The GeoCBI is a modified version of the composite burn index with the advantage of having a measurement of fractional vegetation cover, permitting a better comparison of this index with the burn severity derived from multispectral data. The GeoCBI measures burn severity on a scale of 0–3 and consider the different strata of vegetation by measuring the fraction of cover (FCOV) for vegetation.
Vegetation data	For Case study 1, Queensland regional ecosystem data were used (QSpatial 2018; Queensland Herbarium 2018)	The area of different vegetation classes for the south-east Queensland bioregion was calculated using *GIS* software (Figs 5 and 6)
Fuel load	For Case study 1, regional ecosystem data were used	Fuel estimates were calculated for regional ecosystem classes together with estimates of steady-state fuel for common vegetation groups based on various studies (Appendix 1)

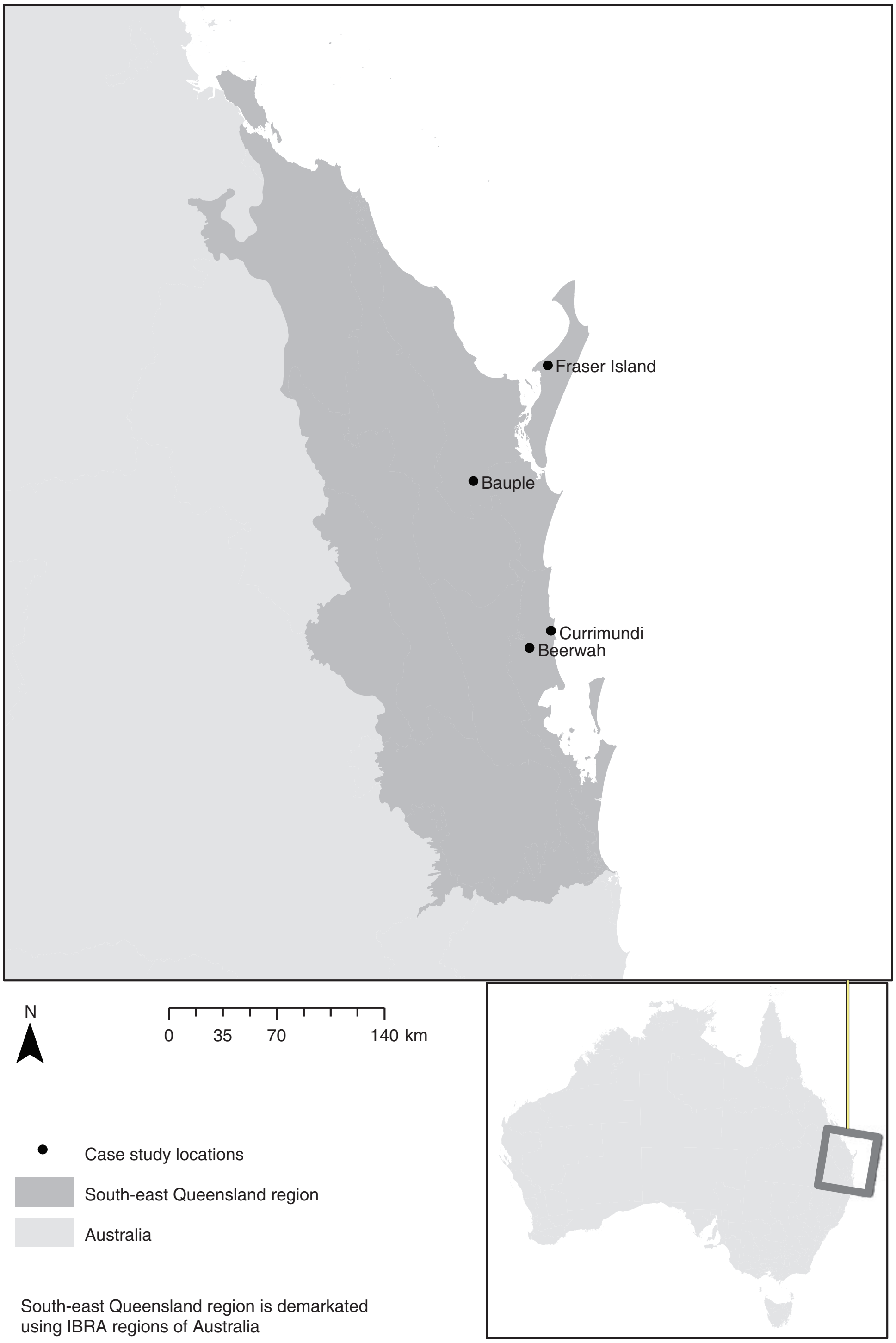


Fig. 4. Study area and the locations of the case studies.

planning a prescribed burn in the study region. Availability of reliable quantitative data at an appropriate map scale could assist in decision-making processes when understanding the risks (likelihood, intensity and effects) associated with fire. Fuel accumulation stratified by vegetation type is important for identifying fire-prone and flammable areas and subsequently identifying priority areas for prescribed burning (QFES 2019). In this case study, we used existing vegetation mapping and information from the literature to derive a fuel load map for the study region. The vegetation of the south-east Queensland bioregion can be broadly classified using Broad Vegetation Groupings (Fig. 5 and Fig. 6) (Neldner *et al.* 2017), which have differing

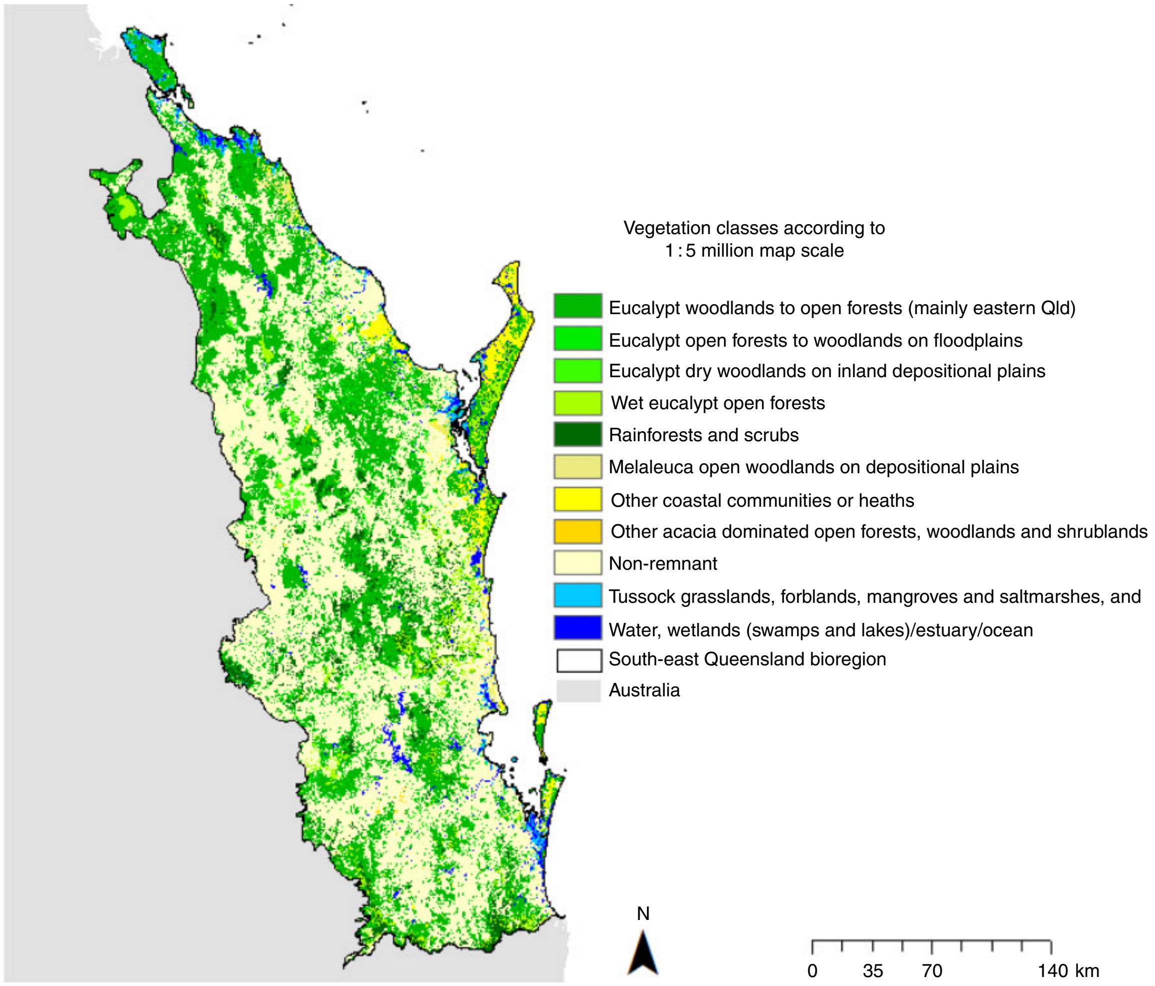


Fig. 5. South-east Queensland bioregion based on Interim Biogeographic Regionalisation (IBRA) for Australia (SA Department of Environment and Water and Natural Resources 2015) selected for this study and the vegetation types (based on broad vegetation types) for the study area.

degrees of flammability and fire management requirements. We used combined regional ecosystem data with broad vegetation group data available at 1, 2 and 5 million map scales. This provided us with datasets with regional ecosystem classes available at 1 : 50 000 map scale for local studies and broad vegetation groups at a coarser map scale (Fig. 5 and Fig. 6).

Fuel biomass tends to show a rapid initial accumulation and load plateaus after several years without fire. Typical fuel accumulation after a fire for key vegetation groupings in the region is provided in Appendix 1. It should be noted that as broad vegetation groupings are used here, there can be significant variation in steady-state fuel among ecosystems within each grouping. For this case study, we linked the theoretical fuel accumulation rates with broad vegetation groupings to produce a map showing fuel distribution (Fig. 7). Although these estimates are used for demonstration purposes, at a local scale, finer-scale vegetation mapping would be used and ideally, fuel loads would be validated with field measurements that incorporate overall fuel hazard (Hines *et al.* 2010). Nevertheless, areas with high fuel biomass can be identified using databases on vegetation types and their distribution with some existing knowledge on fuels. A similar approach was followed for mapping fuel loads and bushfire hazard in Queensland (Newnham *et al.* 2017). Such fuel distribution maps can be further refined using time-since-last-burn information together with burn extent products derived from the analysis of remote sensing data (Case study 2) (Newnham *et al.* 2017). Additional information, including topography and fuel curing, could be added to the fire-prone vegetation map, using additional spatial resources. This could be combined with information on proximity to human settlements to better understand the risk associated with wildfire (e.g. through identifying locations close to human settlements that contain flammable vegetation that has not been burned for a long period).

Case study 2: Mapping burned areas

Conventional mapping of prescribed burning generally records boundaries of the burned area perimeter, irrespective of the

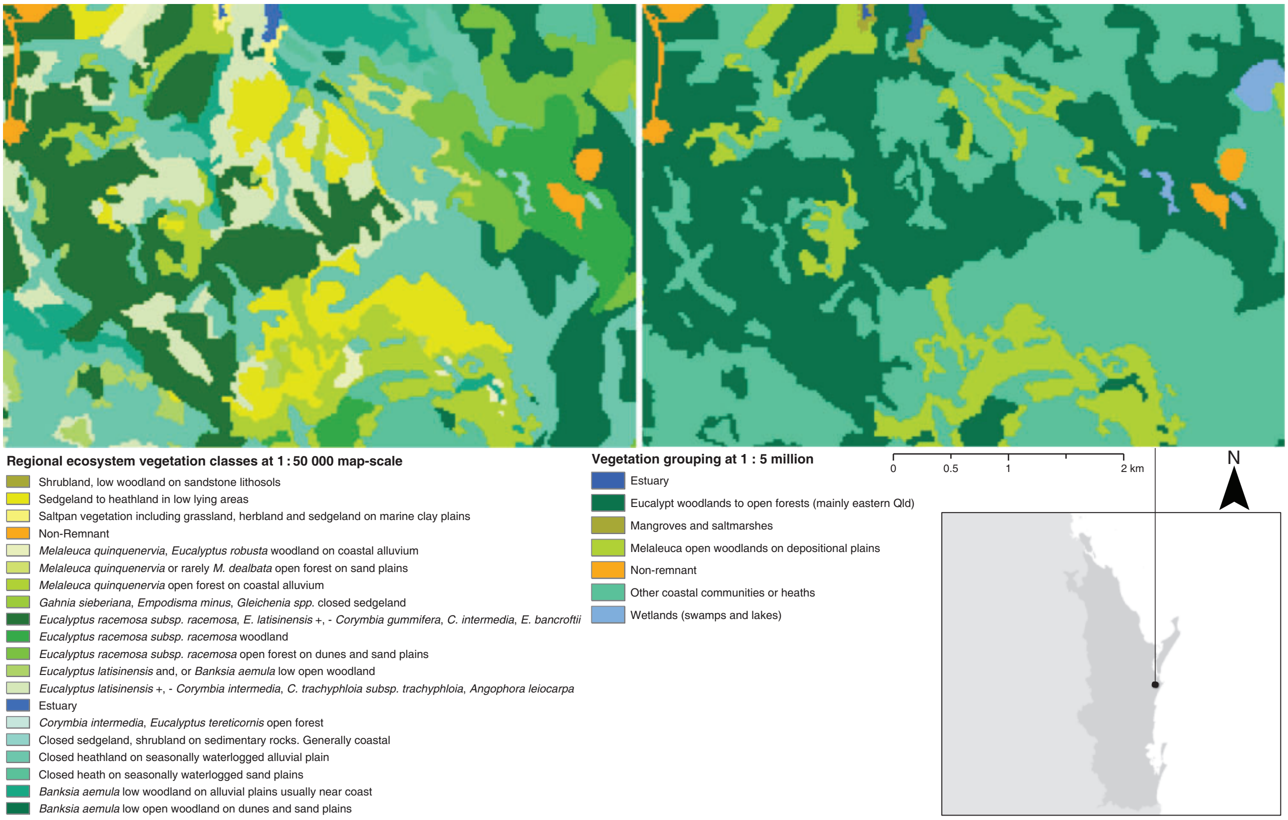


Fig. 6. A comparison of vegetation grouping available at fine and coarse map scale.

heterogeneity within the perimeter. This mapping, which we refer to here as 'perimeter mapping' has many limitations, for example, often unburned patches within the burned perimeter remain unmapped (Kolden *et al.* 2012). Prescribed burn targets often aim to reduce fuel weight by up to 70–75% over 30–60% of the area (Moore and Shields 1996; Gill 2008). However, it is difficult to adequately assess if this aim has been achieved where unburned areas within a prescribed burn boundary remain unmapped (Esplin 2003).

To illustrate the use of remote sensing datasets to more accurately map burned areas, a comparison was made between burnt and unburnt areas on Fraser Island (Fig. 8) using multi-temporal datasets collected from Sentinel 2, Landsat 8 (OLI and TIRS) and Sentinel 1, and burned area products obtained from MCD64A1 and FireCCI (Table 2). The area was burned in July 2017.

A polygon was digitised encompassing the burned area and adjacent unburned area and 500 random locations were generated (Fig. 8*a*). The reclassified differenced normalised burn ratio (dNBR) from Sentinel 2 data was used as the reference for burned areas derived from Landsat 8 dNBR, Landsat 8 differenced land surface temperature (dLST), Sentinel 1 burn index, MCD64A1, and FireCCI (Appendix 3). All these data sources were reclassified as either 'burned' or 'unburned'. Burned and unburned values were extracted for random locations (Fig. 8*a*). As the burned area derived using Sentinel 2 data had the best resolution (Fig. 8*b*), we used this dataset as the reference data for statistical comparisons. A contingency table of true positives, true negatives, false positives and false negatives was generated using *Caret Library of R-statistics* software (Kuhn 2012). The burned area mapped with dNBR derived from Landsat's OLI sensor (Fig. 8*c*) and the difference of pre- and post-fire land surface temperature (LST) (Fig. 8*d*) had the best accuracy levels, whereas the reclassified segmented sum of the normalised difference of pre- and post-fire Sentinel 1 vertical–vertical (VV) and vertical–horizontal (VH) polarisation data (Fig. 8*e*) also had high accuracy levels but with lower kappa values (Table 3). The burned area derived from other sources showed reasonable accuracy levels but with poor kappa values (Fig. 8*f–h*; Table 3).

This case study demonstrated that there are several methods for mapping burned areas to more accurately determine the areas that are actually burnt by fire. This is particularly important where burn aims are to ensure heterogeneity (unburnt patches within the burned area perimeter) and for documenting fire-created mosaics. This also allows more accurate reporting of burned areas when assessing annual burn targets.

Case study 3: Mapping burned areas and subsequent fuel structure changes

Modern remote sensing methods provide opportunities to measure fuel structure and such information is underutilised for planning, monitoring and evaluation of prescribed burns. We investigated the potential use of LiDAR data to assist in mapping changes in fuel heights.

We utilised a long-running fire experiment at the Beerwah scientific area. This experiment has six plots, four of which are

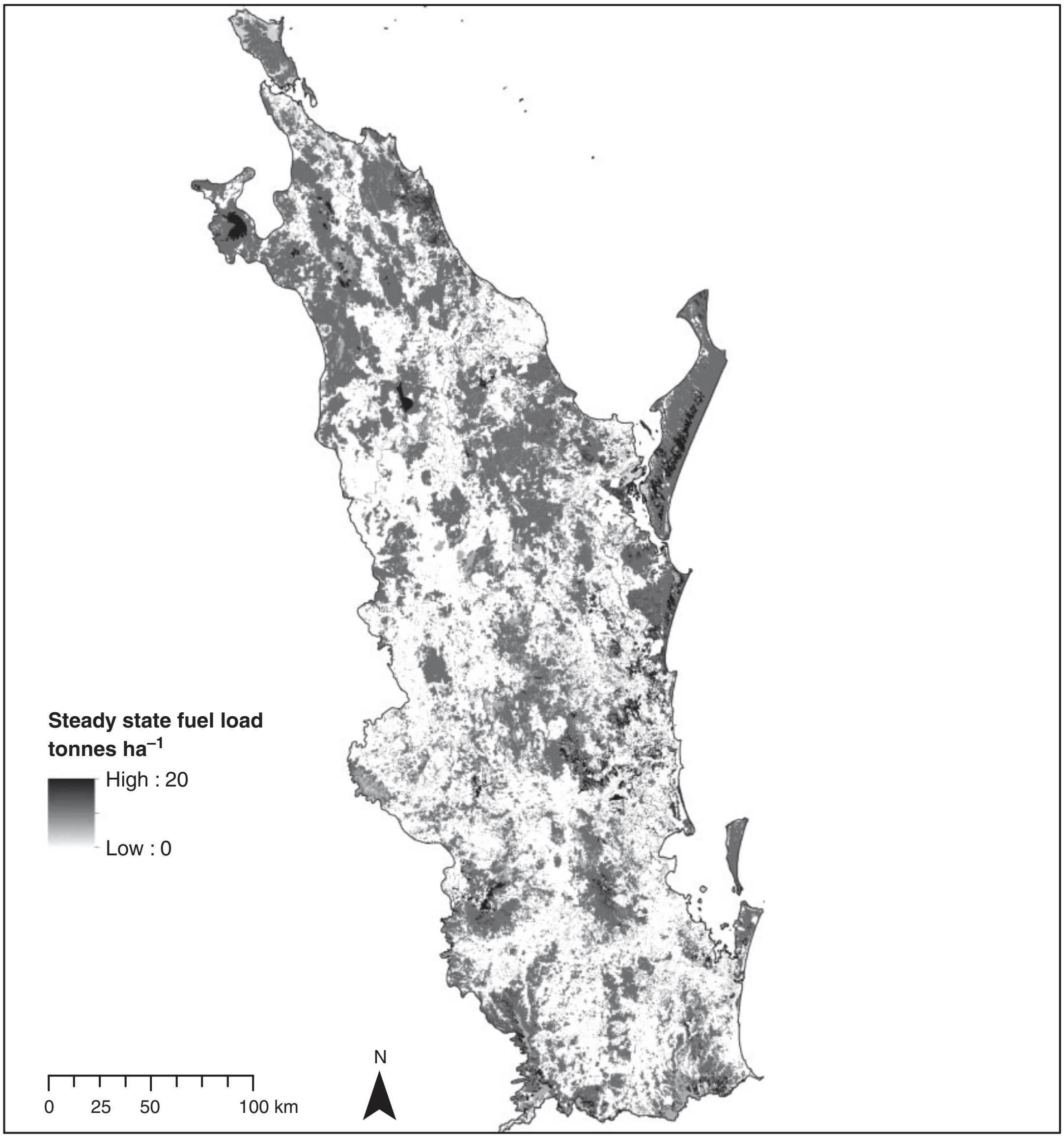
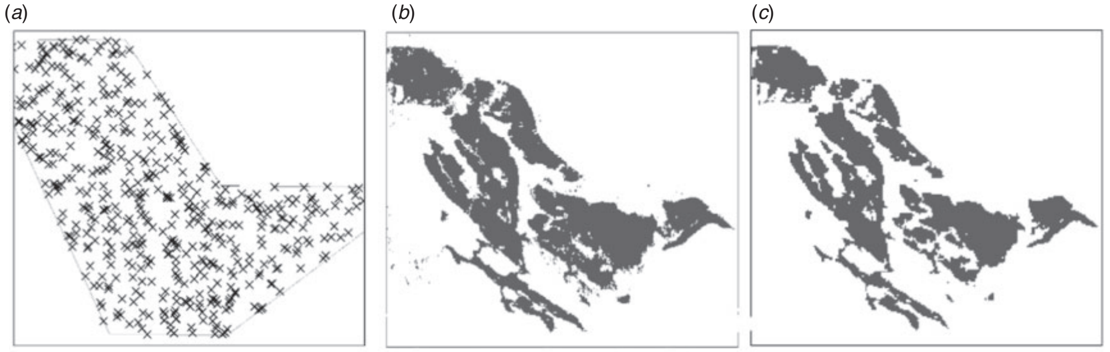


Fig. 7. A potential fuel distribution map for south-east Queensland, based on estimates of steady-state fuel loads for different vegetation classes. Fuel loads were calculated based on Appendix 1.

regularly burnt with prescribed fire, and two where prescribed fire has been excluded since 1973. Three plots (Plots 1–3) are located in open eucalypt forest and three plots (Plots 4–6) are located in wallum heathland. Two plots were burned (with prescribed fire) in 2008 and four plots were burned in 2011 (Fig. 9). The burned area for the two plots burned in 2008 was mapped using products derived from high-resolution multispectral aerial data and pre- and post-burn Landsat data. For 2011, the burned areas were mapped with Landsat data and we analysed LiDAR data to detect a change in vegetation height between 2014 and 2018, following the 2011 burn at four plots.

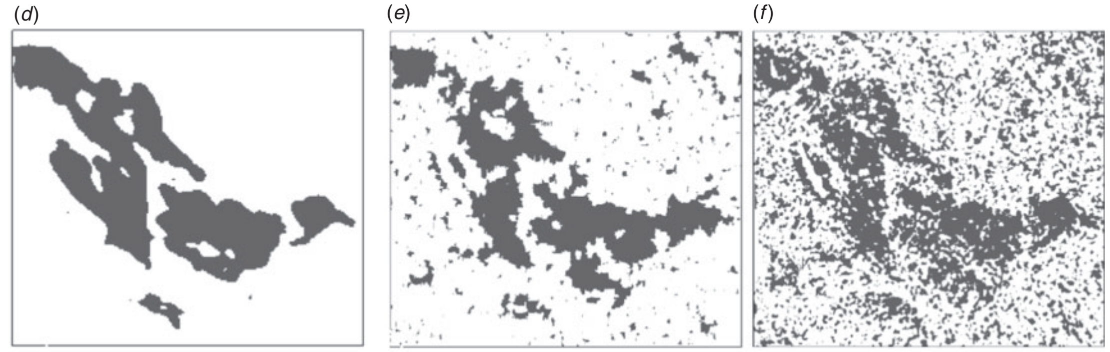
To compare burned area mapping from these datasets for 2008, we used polygons of burned and unburned plots (Fig. 9*a–c*). For all plots, 300 random locations were generated (Fig. 9*a*). Normalised difference vegetation index (NDVI) was derived from the aerial image to map the 2008 burned areas (Fig. 9*b*, *c*). Additionally, the burned plots were mapped using Landsat 5 data after calculating dNBR from pre- and post-burn data (Fig. 9*c*, *d*) for the 2008 and 2011 burns. The LiDAR data were used to calculate the changes in the digital canopy model (dDCM) and in lower vegetation that was less than 0.5 m in height (dLV) (Fig. 9*e*, *f*). These datasets were reclassified using Jenk's natural break methods. Values for all five datasets (Fig. 9 and Table 4) were extracted for 300 random locations. For statistical comparisons, we used burn history information for the plots as reference data separately for 2008 and 2011 (Table 4). A contingency table of true positive, true negative, false positive and false negative was generated using *Caret Library of R-statistics* software.



Sampling locations for comparison of burned area

Burned areas from reclassified dNBR from sentinel 2

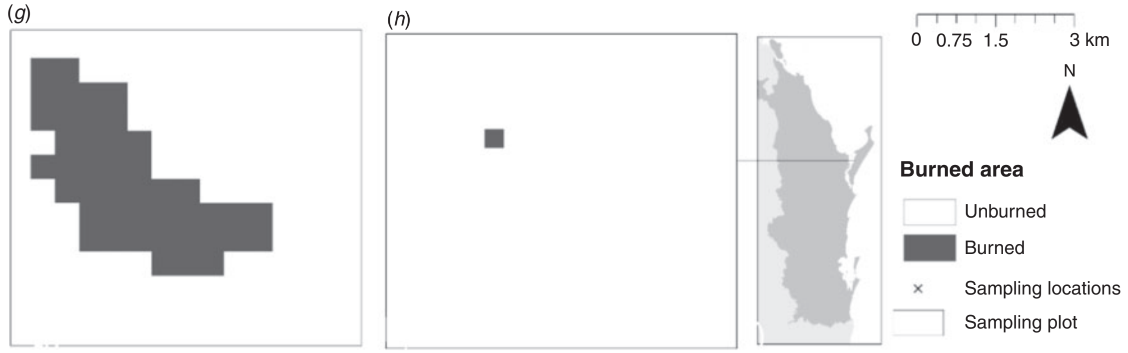
Burned areas from reclassified dNBR from Landsat 8 OLI



Burned areas from reclassified dlST (Landsat 8 TIRS)

Burned areas from reclassified segmented NDRBBvvhh (Sentinel 1)

Burned areas from reclassified NDRBBvvhh (Sentinel 1)



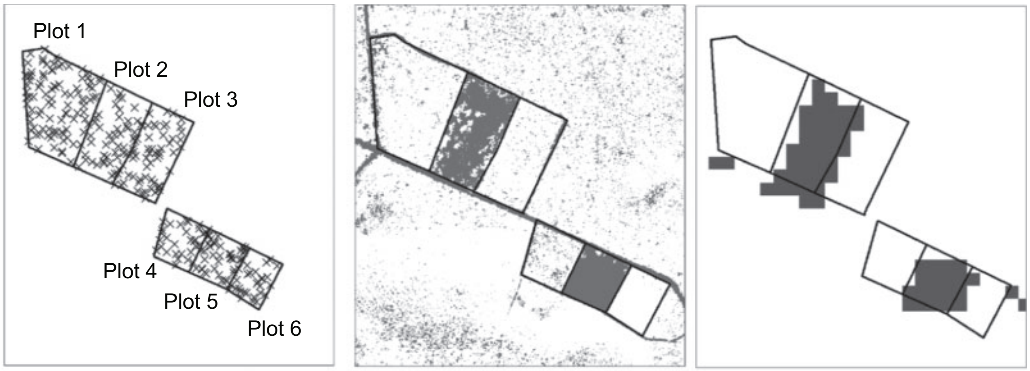
Burned areas from MCD64A1 data

Burned areas from FireCCI data

Fig. 8. A comparison of various products for mapping burned areas. (*a*) Sampling locations for comparing burned area; (*b*) reclassified dNBR calculated from pre and post-burn Sentinel 2 msi data; (*c*) reclassified dNBR calculated from pre and post-burn Landsat 8 OLI data; (*d*) burned area from reclassified Landsat 8 differenced land surface temperature data collected before and immediately after fire; (*e*) reclassified sum of normalised differenced VV and VH polarisation images (pre and post-fire); (*f*) burned area based on the post-burn MCD64A1 burn product; (*g*) burned area in post-burned FireCCI burn product and locations of burn based on active fire database.

Table 3. Comparison statistics of different burned area mapping with the burned area mapped by dNBE derived from Sentinel 2 data

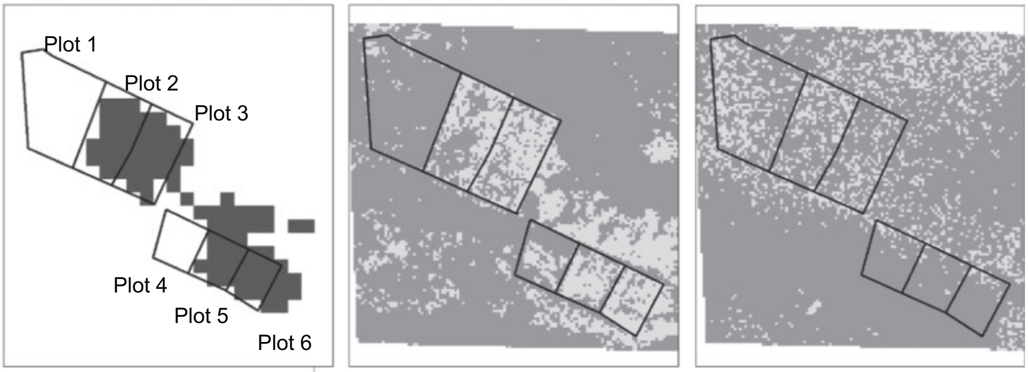
	Accuracy	Kappa	Accuracy *P* value	McNemar *P* value
Reclassified Landsat dNBR	0.91	0.81	1.51×10^{-62}	2.99×10^{-5}
Reclassified Landsat dLST	0.87	0.74	2.27×10^{-48}	8.01×10^{-1}
Reclassified segmented NDRBBvvhh	0.81	0.62	3.49×10^{-30}	6.20×10^{-2}
Reclassified NDRBBvvhh	0.74	0.48	1.85×10^{-14}	5.84×10^{-5}
MCD64a1	0.71	0.41	2.33×10^{-10}	1.35×10^{-1}
FireCCI data	0.57	−0.01	5.90×10^{-1}	1.13×10^{-45}



(*a*) Burn plots and random test locations

(*b*) Burned area mapped with reclassified NDVI of the high-resolution aerial data for 2008 fire

(*c*) Burned area mapped with reclassified dNBR for 2008 burn derived from Landsat data



(*d*) Burned area mapped with reclassified dNBR for 2011 burn derived from Landsat data

(*e*) Areas showing change in lower vegetation height between 2014 and 2018

(*f*) Areas showing change in vegetation height between 2014 and 2018

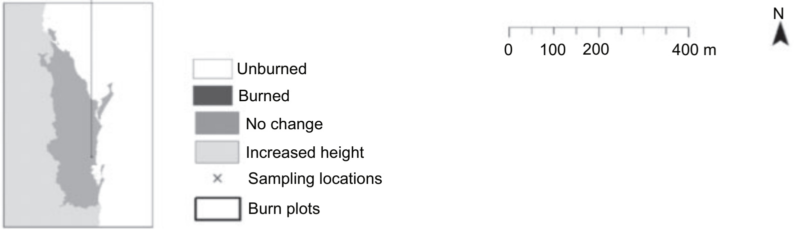


Fig. 9. Monitoring plots in Beerwah scientific area (*a*) with derived products from multispectral images acquired immediately after burning different plots in 2008 and 2011 and multitemporal LiDAR data collected in 2014 and 2018. Images (*b*) and (*c*) show NDVI and dNBR (from Landsat) values acquired immediately after burning two plots (Plots 2 and 5) and they clearly differentiate burned plots from adjacent unburned areas. Image (*d*) shows that dNBR also detected burnt areas following the 2011 burns. Images (*e*) and (*f*) show canopy height change over time where there was a difference in lower vegetation height in recently burnt plots (image (*e*)), but no obvious difference in overall (i.e. canopy) vegetation height between recently burnt and unburnt plots (image (*f*)).

All the methods (NDVI, dNBR for 2008 and 2011) mapped the burned areas with high accuracy and statistical significance (Table 4). The change in overall canopy height model from 2014 to 2018 was not significantly related to burn history (i.e. no difference between plots burned in 2011 and unburnt plots) and had the lowest accuracy, whereas the change in lower vegetation height derived from LiDAR data showed a high level of accuracy (Table 4), suggesting there was significant vegetation growth after the 2011 burn. Presumably, these changes in lower vegetation height resulted in an increase in fuel hazard, especially given the generally high level of flammability associated with these vegetation types during the fire season. This clearly demonstrates the significance of extracting information from multitemporal LiDAR datasets.

Case study 4: Post-burn monitoring to determine burn severity

This case study demonstrates the utility of post-burn data collected in the field, which is a key requirement not only for reviewing and monitoring burn objectives but also for planned burn execution (AFAC 2017*b*). This case study demonstrates the relationship between a geometrically structured composite burn index (GeoCBI) and dNBR at three different locations under different vegetation types and topographic conditions (Fig. 10). The study areas include Currimundi State Forest (Fig. 10*a*), Bauple State Forest (Fig. 10*b*) and Mooloolah River National Park (Fig. 10*c*).

Remote sensing satellites provide useful information about fuel and burned areas, but reliability of all the derived products

Table 4. The comparison statistics of different burned areas and vegetation change with the information on burn plots

Burned area and change mapping method	Plots burned	Accuracy	Kappa	Accuracy *P* value	McNemar *P* value
dNBR Landsat 2008	Plots 2 and 5 were burned in 2008	0.84	0.57	4.46×10^{-2}	4.64×10^{-4}
NDVI Aerial 2008		0.81	0.51	4.77×10^{-1}	3.04×10^{-7}
dNBR Landsat 2011	Plots 2, 3, 5 and 6 were burned in July 2011	0.88	0.76	4.10×10^{-33}	3.25×10^{-9}
Low vegetation changes 2014–18		0.74	0.50	3.95×10^{-11}	2.38×10^{-11}
All vegetation changes 2014–18		0.42	−0.09	1.00	2.90×10^{-13}

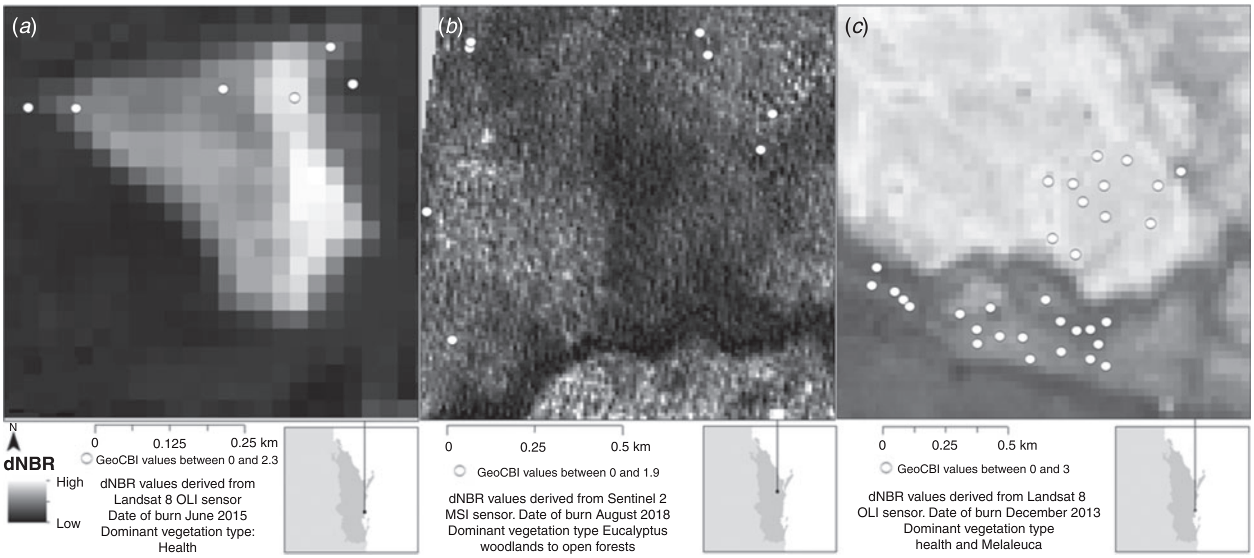


Fig. 10. GeoCBI and dNBR values for burned areas on different vegetation types. GeoCBI values were greater in heathland (up to 2.3 in panel (*a*) and 3 in panel (*c*)) than following prescribed fire in a eucalypt forest (panel (*b*), maximum GeoCBI of 1.9) where the dominant canopy was not scorched by the fire.

depends on the extent to which such information can be validated with field data (Soto-Berelov *et al.* 2015). For assessing the severity of a burn through field data collection, we used a GeoCBI that measures burn severity on a scale of 0–3 (De Santis and Chuvieco 2009). This index was subsequently related to fire indices such as NBR and dNBR derived from multispectral remote sensing data. This allowed assessment of fire severity for each stratum, which can be highly variable depending on the type of fire (e.g. Fig. 11*a* and Fig. 10*b*; burned ground cover while the overstorey is completely unburned). There are several ground-based methods for estimating leaf cover, mainly leaf area index (LAI), which can be combined with GeoCBI data collection (Schaefer 2015). For this study, we used a spherical densitometer to record fractional cover information (Fig. 11*b*).

Fig. 10 shows GeoCBI values for three burned locations with different vegetation types along with dNBR values and demonstrates a variation in the maximum value of GeoCBI depending on burn severity. The covariance analysis of dNBR and GeoCBI values showed a strong correlation in certain vegetation types following wildfire (Table 5). However, at Bauple State Forest this relationship was insignificant because the canopy vegetation remained unburned (giving a low range in severity) potentially owing to the undulating topography of the area. For the heath vegetation in Mooloolah River National Park, the relationship between dNBR and GeoCBI was insignificant mainly (Table 5) because of the sensitivity of NBR to an exposed sandy substrate (see Parker *et al.* 2015). Despite some inconsistency, this case study demonstrates the potential for mapping fire severity with spatial resources. Even in the absence of spatial analysis, we recommend that agencies start routinely recording fire severity data in the field as part of post-fire monitoring and evaluation, as this will assist in determining whether objectives of a burn have been met (e.g. where the aims are to achieve a low-intensity burn).

Discussion and conclusions

Various interrelated aspects of prescribed burning are brought together as a consistent guiding framework and principles offered by the National Burning Project (AFAC 2017*a*). One of the guiding principles for long-term strategic planning is to determine a prescribed burn plan, which can only be achieved through using detailed maps on regional vegetation distribution, their fuel accumulation characteristics, fire occurrence cycle and landscape features (AFAC 2017*a*, 2017*b*). The combination of spatial databases presented in the present study can play a key

Fig. 11. A recently burned area in Bauple State Forest showing (*a*) burned ground cover and unburned tree canopy; and (*b*) a spherical densitometer used to assess canopy cover in the field.

Table 5. Statistical test for the relationship between dNBR and GeoCBI values for different burned areas

Location	Adjusted R^2	n	P value
Mooloolah River National Park, overall, wildfire	0.81	104	<0.001
Mooloolah River National Park, *Eucalyptus racemosa*, wildfire	0.71	25	<0.001
Mooloolah River National Park, heath, wildfire	−0.03	21	0.57
Mooloolah River National Park, *Melaleuca quinquenervia*, wildfire	0.43	39	<0.001
Bauple State Forest, prescribed burn, eucalypt forest	−0.096	12	0.85
Currimundi State Forest, prescribed burn, coastal open woodland	0.83	6	<0.01

role in refining the burn objectives by enabling activity-based performance and outcome-based measures (e.g. that are based on the spatial arrangement of fuel).

The current study has demonstrated the scope for current management practices to be improved through better utilisation of available data resources (Appendix 2 and Appendix 3). This is particularly the case to ensure adequate monitoring and evaluation of prescribed burn objectives and broader targets (Table 6). Use of geospatial datasets can form part of well-designed post-fire monitoring methods, as they produce repeatable and unbiased measures if consistent methodologies are followed. In addition, improved availability and resolution of geospatial data allow a more accurate assessment of fuel conditions, allowing improved predictions of risk associated with

Table 6. Monitoring objectives or targets for fire management agencies in south-east Queensland bioregion that could be addressed under best practice ((AFAC 2017*a*)), how these targets are currently assessed and recommended improvements for future measurements

For QPWS&P, the main agency responsible for prescribed burning on Crown land in the bioregion, specific prescribed burn objectives are listed in a burn proposal created during the planning phase

Examples of key objectives or targets that need to be measured to address best practice	How are these targets measured by Queensland agencies?	Recommended improvements for measuring targets
Burning 5% of public land annually	QPWS&P measures this target by recording burned areas as polygons. This information is recorded easily using GPS and *Desktop GIS*. Data collated so annual percentages can be calculated to determine if targets are met	Burned areas could be more accurately determined (Case study 2). Improved accuracy of fire extent mapping (compared with the perimeter mapping approach currently used) could be achieved using a combination of high-resolution multispectral images, post-burn LiDAR data and field assessments (e.g. walking through burnt areas with a GPS)
Burning 90% of protection zones or key vegetation types annually	QPWS&P uses a combination of vegetation maps such as regional ecosystem maps and creates polygons of burnt areas (e.g. using perimeter maps of the burned areas). This information can be recorded easily using GPS and *Desktop GIS*. Collation of GIS data to determine if targets are met	As above
Achieving an appropriate level of burn coverage, for example: 80% of understorey vegetation burnt in protection zones. Maintaining within-burn heterogeneity (including unburnt patches of vegetation) in ecological burns	Generally not measured in current practices, mainly because of resource constraints	Burn coverage can be mapped using a combination of high-resolution multispectral images, post-burn LiDAR data (e.g. Case study 3) and field assessments (e.g. walking through burnt areas with a GPS)
Maintaining fire-created mosaics through time that are appropriate for the ecosystems present	Generally not measured in current practices, mainly because of resource constraints	Could be determined through the use of multitemporal burned area products derived from high- to moderate-resolution remote sensing data (Case study 2) together with vegetation data (e.g. ecosystem mapping, Case study 1). Targets could be assessed for certain areas (e.g. a given reserve or national park) on an infrequent basis (e.g. every 10 years)
Monitoring fuel hazard and accumulation over time. This could include both vertical continuity of fuels (e.g. protection zones) and spatial continuity of large patches of fuel (e.g. where fuel has accumulated to a high level)	Other than pre-burn fuel assessments, this monitoring is generally not widespread in current practices, mainly because of resource constraints	Continuous areas (measured in hectares) with hazardous fuels could be identified annually so as to guide future burn proposals (e.g. Case study 1). This could be achieved using multitemporal burned products as well as products derived from moderate- to coarse-resolution satellites and the use of these products and GIS mapping to determine time since fire. Use of multitemporal LiDAR data- or photogrammetry-based methods (Olive *et al.* 2020), together with field observations could be used to monitor vertical fuel structure at sites of interest (e.g. adjacent to housing estates)
Achieving low-intensity burns in specific areas, for example, top-disposal burns following timber harvesting in sustainable production zones (e.g. to prevent tree death or damage)	Field assessments (e.g. estimates of intensity) made during a burn	Field assessments could be complemented with fire severity mapping (Case study 4). Field assessments could utilise the GeoCBI and indices such as NBR and dNBR derived from multispectral remote sensing could be used

fire. This information can be incorporated into models (e.g. fire spread), risk-based analysis and decision support tools to allow better protection of assets.

Several data resources exist to enable more accurate mapping of fire regime characteristics (e.g. seasonal and burned area mosaics, severity of burn) and for mapping vegetation types and fuel, providing managers with a better indication of likely fire behaviour, as well as prediction of the effectiveness of prescribed burns. The case studies presented in this paper demonstrate how existing resources could be used in prescribed burn planning and monitoring. For example, information on time since last fire and vegetation types (i.e. regional ecosystems) and their associated fuel can be used to determine if an area meets the criteria for prescribed burning, either before or after routine field assessment. Temporal monitoring of vegetation condition through remote sensing products could enable mapping of seasonal dryness, which could then be used for modifying plans if required (Chuvieco *et al.* 2004). While implementing a prescribed burn, the topographic mapping, combined with local weather maps, can be utilised to determine the lighting pattern on the day. After the burn, various data sets mentioned in this study can be used to map the severity and patchiness of the fire within the broader perimeter and to help determine if the objectives of the burn have been met. These tools should be supplemented with on-ground assessments of the vegetation condition pre and post fire. Table 6 highlights areas where the application of enhanced products could improve on current practices and help meet key fire management targets. Although we have focused on south-east Queensland, the datasets discussed here could be applied in other parts of Australia to allow improved planning, reporting and monitoring by fire managers, as the key objectives or targets that need to be measured to address best practice (e.g. Table 6) are similar in other jurisdictions.

The current practice of burn perimeter mapping excludes information about unburned patches within the burned area. The distribution of unburned patches plays a significant biodiversity role but it can also affect the subsequent severity of a burn during a wildfire event. Similarly, current practices often ignore the vertical distribution of the fuel that can be mapped by modern techniques such as LiDAR. Incorporating ways to track changes in fuel structure (e.g. using LiDAR together with other remote sensing tools) could provide a more complete picture of the overall fuel hazard at a site. A huge archive of temporal LiDAR data is available for different parts of Australia and the cost of collecting LiDAR point clouds from manned aircraft (e.g. AU\$3–12 ha^{-1}) and with drone-mounted scanners is coming down with time (FWPA 2020; Geoscience Australia 2020).

In conclusion, this study recommends the inclusion of the following datasets and practices to assist with future fire management, depending on the availability of resources and feasibility:

- Collection of pre- and post-burn field-based fuel estimates
- Use of LiDAR scans (or other point clouds from photogrammetry) (Olive *et al.* 2020) to determine vertical fuel distribution for a more complete view of fuel hazard
- Measuring the effectiveness of prescribed burns (e.g. burn coverage) and relating with the information on time since the last burn, vegetation types, weather conditions and topography
- Field collection of post-burn indices such as GeoCBI that can be related to remote sensing derived burn indices
- Use of burn indices (e.g. dNBR and dNDVI) derived from multitemporal pre and post-burn multispectral images
- Use of multitemporal burn products available across multiple scales.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

We acknowledge the Butchulla and Gabbi Gabbi Peoples (the Traditional Custodians) of the areas used as examples in this study. The authors are grateful to Dr Jeremy Russell-Smith for his suggestions on the paper. Authors are thankful to Mr Dave Kington, Queensland Parks and Wildlife Service, Department of Environment and Science, for providing critical comments on the paper. The authors gratefully acknowledge the Sunshine Coast Council for providing datasets. The authors are also grateful to the Queensland Government, Geoscience Australia, United Satates Geological Survey (USGS) and European Space Agency (ESA) for making a wide range of data products freely available. This research did not receive any specific funding.

References

AFAC (2017*a*) National guidelines for prescribed burning strategic and program planning. AFAC (Melbourne, Vic., Australia). Available at https://knowledge.aidr.org.au/media/4903/process-map-for-prescribed-burning.pdf [Verified 15 August 2020]

AFAC (2017*b*) Program logic for prescribed burning. Centre of Excellence Prescribed Burning. AFAC (Melbourne, Vic., Australia). Available at https://knowledge.aidr.org.au/media/4905/program-logic-for-prescribed-burning.pdf [Verified 15 August 2020]

Birk EM, Bridges R (1989) Recurrent fires and fuel accumulation in even-aged blackbutt (*Eucalyptus pilularis*) forests. *Forest Ecology and Management* **29**, 59–79. doi:10.1016/0378-1127(89)90056-X

Bridges R (2004) Fine fuel in the dry sclerophyll forests of south-eastern New South Wales. *Australian Forestry* **67**, 88–100. doi:10.1080/00049158.2004.10676212

Burton A, Groenewegen D, Love C, Treloar A, Wilkinson R (2012) Making research data available in Australia. *IEEE Intelligent Systems* **27**, 40–43. doi:10.1109/MIS.2012.57

Chuvieco E, Cocero D, Riano D, Martin P, Martınez-Vega J, de la Riva J, Pérez F (2004) Combining NDVI and surface temperature for the estimation of live fuel moisture content in forest fire danger rating. *Remote Sensing of Environment* **92**, 322–331. doi:10.1016/J.RSE.2004.01.019

Clarkson C, Jacobs Z, Marwick B, Fullagar R, Wallis L, Smith M, Roberts RG, Hayes E, Lowe K, Carah X (2017) Human occupation of northern Australia by 65 000 years ago. *Nature* **547**, 306–310. doi:10.1038/NATURE22968

De Santis A, Chuvieco E (2009) GeoCBI: a modified version of the Composite Burn Index for the initial assessment of the short-term burn severity from remotely sensed data. *Remote Sensing of Environment* **113**, 554–562. doi:10.1016/J.RSE.2008.10.011

Eliott M, Lewis T, Venn T, Srivastava SK (2020) Planned and unplanned fire regimes on public land in south-east Queensland. *International Journal of Wildland Fire* **29**, 326–338. doi:10.1071/WF18213

Esplin B (2003) Report of the Inquiry into the 2002–2003 Victorian Bushfires. Department of Premier and Cabinet. (Melbourne, Vic., Australia) Available at http://royalcommission.vic.gov.au/getdoc/e9af877b-fae7-4dd1-99dc-d696fa2c8c04/INF.018.002.0001.pdf [Verified 15 August 2020]

Fischer WC (1978) Planning and evaluating prescribed fires: a standard procedure. USDA Forest Service, Intermountain Forest Range Experiment Station, General Technical Report no. INT-GTR-43. (Ogden, UT, USA). Available at https://www.fs.fed.us/rm/pubs_int/int_gtr043.pdf [Verified 15 August 2020]

FWPA (2020) Cost benefits for laser-scanned softwood plantations. Available at https://www.fwpa.com.au/rdworks-newsletters/629-cost-benefits-for-laser-scanned-softwood-plantations.html [Verified July 2020]

García MJL, Caselles V (1991) Mapping burns and natural reforestation using Thematic Mapper data. *Geocarto International* **6**, 31–37. doi:10.1080/10106049109354290

Geoscience Australia (2020) Digital elevation data. Available at http://www.ga.gov.au/scientific-topics/national-location-information/digital-elevation-data [Verified July 2020]

Gill AM (1975) Fire and the Australian flora: a review. *Australian Forestry* **38**, 4–25. doi:10.1080/00049158.1975.10675618

Gill A (1998) An hierarchy of fire effects: impact of fire regimes on landscapes. In '3rd International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology Proceedings, vol. 1', November 1998, Luso, Portugal. (Ed. DX Viegas) pp. 129–144. (ADAI: Coimbra, Portugal).

Gill AM (2008) Underpinnings of fire management for biodiversity conservation in reserves. Department of Sustainability Environment. (Melbourne, Vic., Australia) Available at https://www.ffm.vic.gov.au/__data/assets/pdf_file/0012/21090/Underpinnings-of-fire-management.pdf [Verified 15 August 2020]

Gill AM, Zylstra P (2005) Flammability of Australian forests. *Australian Forestry* **68**, 87–93. doi:10.1080/00049158.2005.10674951

Gilroy J, Tran C (2006) A new fuel load model for eucalypt forests in southeast Queensland. In 'Bushfire2006: life in a fire-prone environment: translating science into practice'. Bushfire Conference 2006, Brisbane, 3–6 June 2006, pp. 1–9. (SEQFBC: Brisbane)

Gilroy J, Tran C (2009) A new fuel load model for eucalypt forests in southeast Queensland. In 'Proceedings of the Royal Society of Queensland', University of Queensland, St Lucia, Queensland.

Hines F, Tolhurst KG, Wilson AA, McCarthy GJ (2010) 'Overall fuel hazard assessment guide.' (Victorian Government, Department of Sustainability and Environment: Melbourne,Vic., Australia)

Huesca M, Merino-de-Miguel S, Gonzalez-Alonso F (2013) An intercomparison of satellite burned area maps derived from MODIS, MERIN, SPOT-VEGETATION and ATSR images. An application to the August 2006 Galicia (Spain) forest fires. *Forest Systems* **22**, 222–231. doi:10.5424/FS/2013222-03477

Humber ML, Boschetti L, Giglio L, Justice CO (2018) Spatial and temporal intercomparison of four global burned area products. *International Journal of Digital Earth* **12**, 460–484. doi:10.1080/17538947.2018.1433727

Just TE (1977) Fire control problems of the wallum with particular reference to Cooloola. Technical Paper No. 3. Department of Forestry. (Brisbane, Australia).

Keane RE, Burgan R, van Wagtendonk J (2001) Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire* **10**, 301–319. doi:10.1071/WF01028

Kolden CA, Lutz JA, Key CH, Kane JT, van Wagtendonk JW (2012) Mapped versus actual burned area within wildfire perimeters: characterizing the unburned. *Forest Ecology and Management* **286**, 38–47. doi:10.1016/J.FORECO.2012.08.020

Krebs P, Pezzatti GB, Mazzoleni S, Talbot LM, Conedera M (2010) Fire regime: history and definition of a key concept in disturbance ecology. *Theory in Biosciences* **129**, 53–69. doi:10.1007/S12064-010-0082-Z

Kuhn M (2012) The caret package. Available at https://cran.r-project.org/web/packages/caret/caret.pdf [Verified May 2020]

Leonard J, Newnham G, Opie K, Blanchi R (2014) A new methodology for state-wide mapping of bushfire-prone areas in Queensland. CSIRO. (Canberra, ACT, Australia) Available at https://www.qfes.qld.gov.au/open-data/Bushfire_Prone_Area_Mapping_Report_5_Feb_2014_High_Res.pdf [Verified 15 August 2020]

Lewis T, Debuse VJ (2012) Resilience of a eucalypt forest woody understorey to long-term (34–55 years) repeated burning in subtropical Australia. *International Journal of Wildland Fire* **21**, 980–991. doi:10.1071/WF11003

Lewis T, Reif M, Prendergast E, Tran C (2012) The effect of long-term repeated burning and fire exclusion on above-and below-ground blackbutt (*Eucalyptus pilularis*) forest vegetation assemblages. *Austral Ecology* **37**, 767–778. doi:10.1111/J.1442-9993.2011.02337.X

Miller JD, Knapp EE, Key CH, Skinner CN, Isbell CJ, Creasy RM, Sherlock JW (2009) Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. *Remote Sensing of Environment* **113**, 645–656. doi:10.1016/J.RSE.2008.11.009

Moore P, Shields B (1996) The basis of fuel management on state forest in NSW. *Proceedings of the Linnean Society of New South Wales* **116**, 115–126.

Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, Leonard J, McCaffrey S, Odion DC, Schoennagel T, Syphard AD (2014) Learning to coexist with wildfire. *Nature* **515**, 58–66. doi:10.1038/NATURE13946

Mouillot F, Schultz MG, Yue C, Cadule P, Tansey K, Ciais P, Chuvieco E (2014) Ten years of global burned area products from spaceborne remote sensing – A review: analysis of user needs and recommendations for future developments. *International Journal of Applied Earth Observation and Geoinformation* **26**, 64–79. doi:10.1016/J.JAG.2013.05.014

Mutlu M, Popescu SC, Stripling C, Spencer T (2008) Mapping surface fuel models using lidar and multispectral data fusion for fire behavior. *Remote Sensing of Environment* **112**, 274–285. doi:10.1016/J.RSE.2007.05.005

Neldner V, Wilson B, Dillewaard H, Ryan T, Butler D (2017) 'Methodology for survey and mapping of regional ecosystems and vegetation communities in Queensland: Version 4.0.' (Department of Science, Information Technology and Innovation: Brisbane, Qld, Australia)

Newnham G, Opie K, Leonard J (2017) A methodology for state-wide mapping of annual fuel load and bushfire hazard in Queensland. CSIRO. (Brisbane, Qld, Australia) Available at https://publications.csiro.au/rpr/download?pid=csiro:EP175130&dsid=DS4 [Verified 15 August 2020]

Olive K, Lewis T, Ghaffariyan MR, Srivastava SK (2020) Comparing canopy height estimates from satellite-based photogrammetry, airborne laser scanning and field measurements across Australian production and conservation eucalypt forests. *Journal of Forest Research* **25**, 108–112. doi:10.1080/13416979.2020.1735671

Parker BM, Lewis T, Srivastava SK (2015) Estimation and evaluation of multidecadal fire severity patterns using Landsat sensors. *Remote Sensing of Environment* **170**, 340–349. doi:10.1016/J.RSE.2015.09.014

Parr CL, Andersen AN (2006) Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. *Conservation Biology* **20**, 1610–1619. doi:10.1111/J.1523-1739.2006.00492.X

QFES (2019) Bushfire prevention and preparedness. Queensland Fire and Emergency Services. (Brisbane, Qld, Australia) Available at https://www.qfes.qld.gov.au/about/Documents/QFES-Bushfire-Report.pdf [Verified 15 August 2020]

QPWS (2013) Planned burn guidelines – South-east Queensland Bioregion of Queensland. Department of National Parks, Recreation, Sport and Racing. (Brisbane, Qld, Australia)

QPWS&P (2011) Strategy 1: Natural and cultural resource management. In 'GreatSandy Region Management Plan', pp. 23–54. (QPWS&P: Brisbane, Qld, Australia))

QPWS&P (2019) Enhanced fire management program, Queensland Parks & Wildlife Service 2019–2023 (2019), Internal document. (QPWS&P: Brisbane, Qld, Australia)

QSpatial (2018) Vegetation management regional ecosystem map – Version 10.1. Available at http://qldspatial.information.qld.gov.au/catalogue/

Queensland Government (2018) Bioregional planned burn guidelines. Available at https://www.npsr.qld.gov.au/managing/planned-burn-guidelines.html [Verified 15 August 2020]

Queensland Government (2020) Queensland spatial catalogue – QSpatial. Available at http://qldspatial.information.qld.gov.au/catalogue/ [Verified 15 August 2020]

Queensland Herbarium (2018) Regional Ecosystem Description Database (REDD), version 10.1. Available at https://www.qld.gov.au/environment/plants-animals/plants/ecosystems/descriptions/download [Verified 15 August 2020]

Rollins MG, Keane RE, Parsons RA (2004) Mapping fuels and fire regimes using remote sensing, ecosystem simulation, and gradient modelling. *Ecological Applications* **14**, 75–95. doi:10.1890/02-5145

Russell-Smith J, Whitehead PJ, Cook GD, Hoare JL (2003) Response of eucalyptus-dominated savanna to frequent fires: lessons from Munmarlary, 1973–1996. *Ecological Monographs* **73**, 349–375. doi:10.1890/01-4021

Russell-Smith J, Evans J, Edwards AC, Simms A (2017) Assessing ecological performance thresholds in fire-prone Kakadu National Park, northern Australia. *Ecosphere* **8**, e01856. doi:10.1002/ECS2.1856

SA Department of Environment and Water and Natural Resources (2015) IBRA Region Australia Version 7.0 – PED. Available at https://data.gov.au/data/dataset/9791362e-bfb3-4d13-8a7a-dd10f25c4d84 [Verified August 2020].

Schaefer MT (2015) Measurement of above-ground biomass. In 'AusCover good practice guidelines: A technical handbook supporting calibration and validation activities of remotely sensed data products, Version 1.2.' (Eds A Held, S Phinn, M Soto-Berelov, S Jones) pp. 208–226. (TERN AusCover: Brisbane, Qld, Australia))

Soto-Berelov M, Jones S, Woodgate W (2015) Review of validation standards of biophysical Earth Observation products. In 'AusCover good practice guidelines: A technical handbook supporting calibration and validation activities of remotely sensed data products, Version 1.2.' (Eds A Held, S Phinn, M Soto-Berelov, S Jones) pp. 8–32. (TERN AusCover: (Brisbane, Qld, Australia))

Srivastava SK (2015) Availability and uses of spatial databases for research and management of K'gari–Fraser Island. *Australasian Journal of Environmental Management* **22**, 233–260. doi:10.1080/14486563.2015.1028108

Srivastava SK, King L, Mitchell C, Wiegand A, Carter RW, Shapcott A, Russell-Smith J (2013) Ecological implications of standard fire-mapping approaches for fire management of the World Heritage Area, Fraser Island, Australia. *International Journal of Wildland Fire* **22**, 381–393. doi:10.1071/WF11037

Tanner L (2010) Declaration of open government. Department of Finance (Australia). Available at https://parlinfo.aph.gov.au/parlInfo/search/display/display.w3p;query=Id:%22media/pressrel/AKCX6%22 [Verified 15 August 2020]

Tolhurst K, Flinn D (1992) 'Ecological impacts of fuel reduction burning in dry sclerophyll forest.' (Department of Conservation and Environment: Melbourne, Vic., Australia)

Tran C, Wild C (2000) 'A review of current knowledge and literature to assist in determining ecologically sustainable fire regimes for the south-east Queensland region.' (Griffith University and Queensland Fire and Biodiversity Consortium: Brisbane, Qld, Australia)

Turner D, Ostendorf B, Lewis M (2008) An introduction to patterns of fire in arid and semi-arid Australia, 1998–2004. *The Rangeland Journal* **30**, 95–107. doi:10.1071/RJ07039

Walker J (1981) Fuel dynamics in Australian vegetation. In 'Fire and the Australian biota'. (Eds AM Gill, RH Groves, IR Noble) pp. 101–127. (Australian Academy of Science: Canberra, ACT, Australia)

Watson P (2001) 'The role and use of fire for biodiversity conservation in south-east Queensland: fire management guidelines derived from ecological research'. (South-east Queensland Fire & Biodiversity Consortium: Brisbane, Qld, Australia) Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.622.8421&rep=rep1&type=pdf [Verified 15 August 2020]

Yebra M, Marselis S, Van Dijk A, Cary G, Chen Y (2015) Using LiDAR for forest and fuel structure mapping: options, benefits, requirements and costs. Report No. 2015.064. (Melbourne, Vic, Australia) Available at https://www.bnhcrc.com.au/sites/default/files/managed/downloads/using_lidar_for_forest_and_fuel_structure_mapping_final.pdf [Verified 15 August 2020]

Appendix 1. Broad vegetation groups in south-east Queensland, the percentage areas that they occupy in the region (total area of 6 244 382 ha), an estimate of steady-state fuel loads based on the literature (Just 1977; Walker 1981; Birk and Bridges 1989; Gilroy and Tran 2009; Leonard *et al.* 2014) and maximum fuel loads in long unburnt conditions reported in Leonard *et al.* (2014)

Where no estimate of steady-state fuel load was available, an estimate was made by the authors. Recommended prescribed burn intervals are provided based on associated regional ecosystems (Watson 2001; Queensland Herbarium 2018; QSpatial 2018)

Major vegetation classes	% of south-east Queensland region	An estimate of steady-state fuel load (tonnes ha^{-1})	Recommended intervals
Eucalypt woodlands to open forests (mainly eastern Qld)^{A}	31.8	12–30	3–25 years (3–6 years grassy understorey; 7–25 years shrubby understorey)
Eucalypt open forests to woodlands on floodplains	2.2	9–19	3–10 years (prescribed burning avoided in some fringing vegetation)
Eucalypt dry woodlands on inland depositional plains^{B}	0.7	9–19	3–10 years
Wet eucalypt open forests^{B,C}	2.7	20–28	4–8 years (grassy understory); 8–20 years (shrubby understorey); minimum interval of 20 years for certain ecosystems (e.g. *Eucalyptus grandis* tall open forest)
Rainforests and scrubs^{B}	4.4	5.6–10	Prescribed burning generally avoided
Melaleuca open woodlands on depositional plains^{D}	1.3	17–33	6–20 years (varies depending on understorey)
Other coastal communities or heaths^{B,E}	2.7	12–27	7–20 years (although generally avoided in certain ecosystems, e.g. fore-dune complex)
Other acacia dominated open forests, woodlands and shrublands	0.1	8–10	4–25 years (but generally avoided in *Acacia harpophylla* scrubs)
Non-remnant^{D}	50.8	5	Varies depending on land use
Tussock grasslands, forblands, mangroves and saltmarshes, sand	1.3	3–5	Mangrove and saltpan vegetation not deliberately burnt. Certain tussock grasslands 3–20 years, but prescribed burning avoided in certain coastal grasslands and forblands
Water, wetlands (swamps and lakes), estuary, ocean	2	0	Not deliberately burnt, but wetlands are sometimes burnt in association with the surrounding vegetation

[A] Gilroy and Tran (2009).
[B] Walker (1981).
[C] Birk and Bridges (1989).
[D] Leonard *et al.* (2014).
[E] Just (1977).

Appendix 2. Key remote sensing satellites and sensor characteristics for burned area mapping

	Satellite	Sensor and data availability	Spatial resolution	Other characteristics (all sensors detect visible and near-infrared spectrum)	Fire management
1	Landsat series^{A}	MSS, TM, ETM, OLI freely accessible	30 m (80 m for MSS)	Shortwave IR and thermal bands. Data available since the 1970s	Routine use of pre- and post-burn indices will provide information about burn performance, especially the distribution of unburnt patches within a burn area and accurate per-pixel information about time since burn
2	Sentinel 2^{A}	MSI freely accessible	10–20 m	Shortwave IR band, shorter revisit period increases chances of getting cloud-free data	
3	SPOT	HRV/HVIR SPOT vegetation freely accessible if the dataset is older than 3 months	10–20 m	Data available since 1986 SWIR band (SPOT4)	
4	Terra	ASTER freely accessible	15–30 m	Data available since 2000 SWIR and thermal bands	

(*Continued*)

(Continued)

	Satellite	Sensor and data availability	Spatial resolution	Other characteristics (all sensors detect visible and near-infrared spectrum)	Fire management
5	Worldview2	Multispectral	2 m	Additional spectral bands for vegetation (red edge and yellow)	Routine use of pre- and post-burn indices will provide deeper insight into burn performance, especially the distribution of unburnt patches within a burn area and accurate per-pixel information about time since burn
6	Worldview3	Multispectral and SWIR	1.2–4.1 m	Eight SWIR bands	
7	Planet Laboratories constellation (130+ Planetscope, 5 Rapideye, and 13 Skysat)	Multispectral free, but limited download for research	0.8–5 m	Vast amount of high-resolution data at very high temporal resolution	
8	Terra and Aqua	MODIS freely accessible	250, 500 and 1000 m	Data available since 2000 Thermal and SWIR bands; daily data collection	Routine use of pre- and post-burn indices will provide information about the distribution of fuel over a wider area and the need for creating barriers such as trails. This dataset will also be used for prioritising areas for prescribed burning
9	NOAA	AVHRR freely accessible	1100 m	Data available since 1981; daily data collection thermal band	

[A] Archived and near real-time analysis-ready data are available with Geoscience Australia.

Appendix 3. Key burned area products from remote sensing images

	Burn products	Sensor, algorithm, and website	Temporal coverage and period	Spatial extent and resolution
1	Global Burn Surface (GBS)	NOAA AVHRR Multitemporal multithreshold algorithm for fire probability http://forobs.jrc.ec.europa.eu/products/fire_probability_82-99/global-prob_82-99.php [Verified 15 August 2020]	1982–99, weekly	Global, 8 km
2	Global Land Products for Carbon Model Assimilation (Globcarbon)	ATSR-2, AATSR, MERIS, and VEGETATION http://due.esrin.esa.int/page_project43.php [Verified 15 August 2020]	April 1998 to December 2007, monthly	Global, 1 km
3	Global Fire Emission Database version 3 (GFED3)	MODIS 500m, TRIM/VIRS, ATSR https://daac.ornl.gov/VEGETATION/guides/global_fire_emissions_v3.1.html [Verified 15 August 2020]	July 1996 to present, monthly	Global, 2 km
4	Burnt Area 300 (BA300)	SPOT Vegetation and Proba-V; a sudden change in vegetation index https://land.copernicus.eu/global/products/ba [Verified 15 August 2020]	April 1999 to present, 10-day interval	Global, April 1999 to April 2014 at 1 km and April 2014 to present at 300 m
5	Global Burnt Area-2000 (GBA2000)	SPOT Vegetation A series of regional algorithms http://forobs.jrc.ec.europa.eu/products/burnt_areas_L3JRC/GlobalBurntAreas2000-2007.php [Verified 15 August 2020]	2000–07, monthly	Global, 1 km
6	L3JRC	SPOT Vegetation A modified version of GBA2000 https://ec.europa.eu/jrc/en/scientific-tool/global-burnt-area-2000-2007 [Verified 15 August 2020]	2000–07, daily	Global, 1 km

(*Continued*)

(Continued)

	Burn products	Sensor, algorithm, and website	Temporal coverage and period	Spatial extent and resolution
7	MODIS Grassland Curing	MODIS Curing values are derived from surface reflectance estimates in up to seven spectral bands that are derived from cloud-free MODIS observations in an 8-day window http://www.auscover.org.au/datasets/grassland-curing/ [Verified 15 August 2020]	2000–16, 8 days	Australia, 500 m
8	ATSR World Burned Surface Atlas (GLOBSCAR)	ERS2-ATSR2 K1 and E1 algorithms http://due.esrin.esa.int/page_project24.php [Verified 15 August 2020]	>2000, monthly	Global, 1 km
9	Fire Climate Change Initiative (FireCCI)	ENVISAT MERIS Maximum composites of spectral indices characterised by low values of temporal standard deviation in space and associated with MODIS hot spots https://geogra.uah.es/fire_cci/ [Verified 15 August 2020]	2000–17	Global, 300 m
10.	MODIS/Terra and Aqua Combined Burned Area Monthly L3 Global 500 m SIN Grid V006 (MCD45A1 and MDC64A1)	MODIS Terra and Aqua, burn sensitive vegetation index MCD45A1 is modelled on a temporally rolling basis of the bidirectional effects in the daily MODIS time series to identify persistent changes in surface reflectance due to burning MCD64A1algorithm is a hybrid one that supplements daily surface reflectance imagery with daily active fire data https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd64a1_v006 [Verified 15 August 2020]	November 2000 to present, monthly	Global, 500 m
11.	MODIS/Aqua+Terra Thermal Anomalies/Fire locations (MCD14ML)	MODIS, Thermal anomalies https://earthdata.nasa.gov/c5-mcd14dl [Verified 15 August 2020]	November 2000 to present, 1–2 days	Global, 1 km
12.	Fire Information for Resource Management System (FIRMS)	Suomi-NPP VIIRS, hybrid thresholding and contextual algorithm using radiometric signals from 4–11 bands https://firms.modaps.eosdis.nasa.gov/ [Verified 15 August 2020]	January 2012 to present, 12 h	Global, 375 m and point locations
13.	Queensland Annual Fire Scars	Derived from all available Landsat and Sentinel-2 images http://www.auscover.org.au/purl/landsat-fire-scars-qld [Verified 15 August 2020]	1987–2015 from Landsat 2016 from Sentinel-2 and Landsat, yearly	Queensland, 30 m