SPECIAL ISSUE

CSIRO PUBLISHING

International Journal of Wildland Fire **2020**, *29*, 326–338
https://doi.org/10.1071/WF18213

Planned and unplanned fire regimes on public land in south-east Queensland

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Abstract. Land management agencies in Queensland conduct planned burning for a variety of reasons, principally for management of fuels for human asset protection and biodiversity management. Using Queensland Parks and Wildlife Service's archived manually derived fire reports, this study considered the individual components of the fire regime (extent, frequency and season) to determine variation between planned and unplanned fire regimes in south-east Queensland. Overall, between 2004 and 2015, planned fire accounted for 31.6% and unplanned fire 68.4% of all fire on Queensland Parks and Wildlife Service state-managed land. Unplanned fire was more common in spring (September–October), and planned fire was more common in winter (June–August). Unplanned fire affected 71.4% of open forests and woodlands (148 563 ha), whereas 58.8% of melaleuca communities (8016 ha) and 66.6% of plantations (2442 ha) were burnt with planned fire. Mapping fire history at a regional scale can be readily done with existing publicly available datasets, which can be used to inform the assessment of planned burning effectiveness for human asset protection and the management of biodiversity. Fire management will benefit from the continued recording of accurate fire occurrence data, which allows for detailed fire regime mapping and subsequent adaptive management of fire regimes in the public domain.

Additional keywords: controlled burn, ecological burn, fire mapping, prescribed fire, wildfire.

Received 30 November 2018, accepted 19 July 2019, published online 27 August 2019

Introduction

Fire is a common land management tool in south-east Queensland (SEQ). Planned fire (also referred to as prescribed or controlled fire) is defined as fire that is planned by managers, and unplanned fire (also referred to as wildfire or bushfire) is fire not planned by managers. On public land in this region, planned fire is most commonly used to reduce the risk of unplanned fire, through reducing fuel loads and modifying fuel structure, and for encouraging biodiversity through the potential ecological benefits for flora and fauna in specific ecosystems (Price *et al.* 2015; Tolhurst and McCarthy 2016). In SEQ, the Queensland Parks and Wildlife Service (QPWS) is the main land management agency responsible for planned burning on state–government-managed public land. The QPWS is responsible for managing ~205 145 ha of public land in the SEQ region. Despite known benefits of planned burning in certain ecosystems, fire is not applied to all ecosystems equally, mainly owing to the lack of resources available for planned burning over large areas, and to the varying fire requirements of different vegetation types (Bradstock *et al.* 2012; Queensland Parks and Wildlife Service 2012; Queensland Herbarium 2013; Price *et al.* 2015; Croft *et al.* 2016).

Fire regime was initially defined by Gill (1975) to incorporate fire frequency, intensity and season of occurrence. Later definitions have incorporated the extent and pattern of burning across the landscape (Gill 1998; Sullivan *et al.* 2012; Murphy *et al.* 2013). These are key variables that fire managers take into account when managing the land with fire, along with other important factors that determine when a burn can be carried out (e.g. weather conditions, fuel moisture, fuel load and arrangement). The fire regime is constructed from historical fire practices and plant species characteristics in a particular vegetation community, which is strongly driven by climate and edaphic variables (Gill 1975; Queensland Parks and Wildlife Service 2012; South-east Queensland Fire and Biodiversity Consortium 2014). Variations in fire regime in Australia are primarily related to differences in seasonal conditions, available moisture and dominance by either woody or herbaceous plant cover (Gill 1979; Cary *et al.* 2003; Bradstock 2010; Gill *et al.* 2012; Murphy *et al.* 2013). A key aim for many land managers is to maintain an appropriate fire regime using planned fire to ensure natural ecosystems are preserved. To use planned fire in a way that is positive for the environment in SEQ, there needs to be an understanding of how often and during which season and weather conditions that fire should be applied to the landscape within specific areas or ecosystems. Ecological literature suggests that it is important to ensure variation in fire regimes (e.g. varying intervals between fires and seasons in which fires occur) to encourage biodiversity (Gill *et al.* 2012; Sullivan *et al.* 2012; Kelly *et al.* 2016). An inappropriate fire regime for a particular ecosystem can have negative impacts on biodiversity (Gill 1975; Cary *et al.* 2003; Gill *et al.* 2012).

Recommended fire regimes for biodiversity conservation are, in most cases, based primarily on the plant community responses, and are broadly defined (e.g. Lawes and Clarke 2011; Duff *et al.* 2013; Clarke *et al.* 2015). For example, in Queensland, operational management guidelines for dry sclerophyll forests recommend burning at intervals of between 4 and 20 years, with an emphasis on variability of fire intervals (Queensland Herbarium 2016; Neldner *et al.* 2017*a*). These recommended intervals vary among different vegetation types. On the basis of broad vegetation groupings, Neldner *et al.* (2017*a*) suggested frequencies of: 6–7 years for coastal fringing forests and headlands; 2–3 years for grasslands communities; 7–20 years for heath communities; 6–20 years for melaleuca communities; 7–25 years for open forests and woodlands; 20–100 years for wet tall open forests; and no fire for mangroves and saltmarsh vegetation, rainforests, dry vine forests, and brigalow, riparian, foredune, coral cay island and beach ridge communities. However, often there is little assessment of the recent history of fires in SEQ to adequately determine whether fire regimes are managed in agreement with current ecological recommendations.

Unplanned fire can be ignited by either natural (e.g. lightning) or human causes (e.g. escaped burns, accidental ignition from industry or recreation), and these fires are managed by QPWS on state-managed public land, with support from the Queensland Fire and Emergency Service, Rural Fire Service Queensland and other relevant government departments. There have been few attempts to determine the area of SEQ that has been burnt by unplanned fire, but such information is critical when trying to piece together the historic regime (i.e. the past occurrences of any fire over the past 100 years) for a given area. Unplanned fire commonly occurs across most vegetation types in SEQ and can occur throughout the year, when conditions are dry. However, unplanned fires occur more often during the drier months before the summer rainfall begins, when humidity is low (Luke and McArthur 1978; Browne and Minnery 2015), and when there is an increased chance of lightning strikes from dry storms (Gill 1979; Gill *et al.* 2012; Leeson 2013). Unplanned fires are often difficult to contain and often cover a greater extent than planned fires (Bowman *et al.* 2009; Bradstock *et al.* 2010).

The Australian Federal Government has a 'Prescribed Burning Performance Measurement Framework' for all states and territories to follow (Australasian Fire and Emergency Service Authorities Council 2018). This framework includes jurisdiction, reporting period and certain measures, including: number of planned burns conducted; area burnt by prescribed fire; percentage of area burnt *v.* annual target; 5-year average total area of hazard reduction work completed; number of homes protected; average cost per hectare; and proportion of fire management zones treated (Australasian Fire and Emergency Service Authorities Council 2018). QPWS implements planned burns annually, and has defined fire management zones (Table 1). For example, the target for 2017 planned burns was 632 000 ha for the whole State of Queensland, and QPWS achieved 225 411 ha of fuel reduction planned burning for protection of life and property and biodiversity (Department of National Parks, Sport and Racing 2018, p. 13). QPWS noted that 'unfavourable planned burn conditions and the transition to the spring–summer fire risk period impacted delivery of planned burns in many areas', and that 'this service standard reflects the 2009 Victorian Bushfires Royal Commission recommendation that a 5% target for planned burning of the state should be established'.

Table 1. Queensland Parks and Wildlife Service fire management zone areas and proportions in south-east Queensland

Exclusion: excludes fire totally. Protection: provides a high level of protection to life, property and infrastructure. Reference: for monitoring long-term effects of fire regimes, wildfires or fire exclusion on nature conservation values. Rehabilitation: combats a threatening process that cannot be addressed by the usual fire management practices. Special conservation: maintains the natural role of fire as an ecological process. Sustainable production: maintains the sustainable production and use of forest products (e.g. timber, foliage, pasture). Wildfire mitigation: increases the likelihood of controlling a wildfire in strategically important areas within a reserve (Department of National Parks, Recreation, Sport and Racing 2013)

Fire management zone	Area (ha)	Proportion of all fire management zones (%)
Exclusion	1246	1.3
Protection	3175	3.4
Reference	484	0.5
Rehabilitation	5015	5.4
Special conservation	2363	2.5
Sustainable production	48 700	52.0
Wildfire mitigation	32 636	34.9

In 2017, 1.74% of the entire QPWS estate (12 936 000 ha) was burnt using planned burns. Additionally, QPWS had a 2017 target of burning 90% of protection and wildfire mitigation zone fuel management on QPWS-managed estate to protect life and property, and achieved 85%. For their reporting period in 2017, QPWS implemented 67 planned burns (225 411 ha), and responded to 141 wildfires (284 783 ha). In light of this, we assessed how much planned burning in the SEQ region has been completed, and if QPWS are meeting planned burn targets. In relation to fire as an ecological process, specific burning by QPWS allows for natural ecological processes incorporated in the fire management strategies for each area managed by QPWS as recommended fire regimes (P. Leeson, pers. comm., 21 November 2018); these are outlined in their fire management guidelines (Queensland Parks and Wildlife Service 2012; Department of National Parks, Sport and Racing 2015; Queensland Herbarium 2016).

Fire managers need to be aware of the past fire history (i.e. the spatial and temporal pattern of fire at a given location) to then apply and manage fire in the best possible way. To do this, fire managers need to have up-to-date spatial distributions of past fire events to assess the extent of both planned and unplanned fire, the frequency of fire and the seasons in which

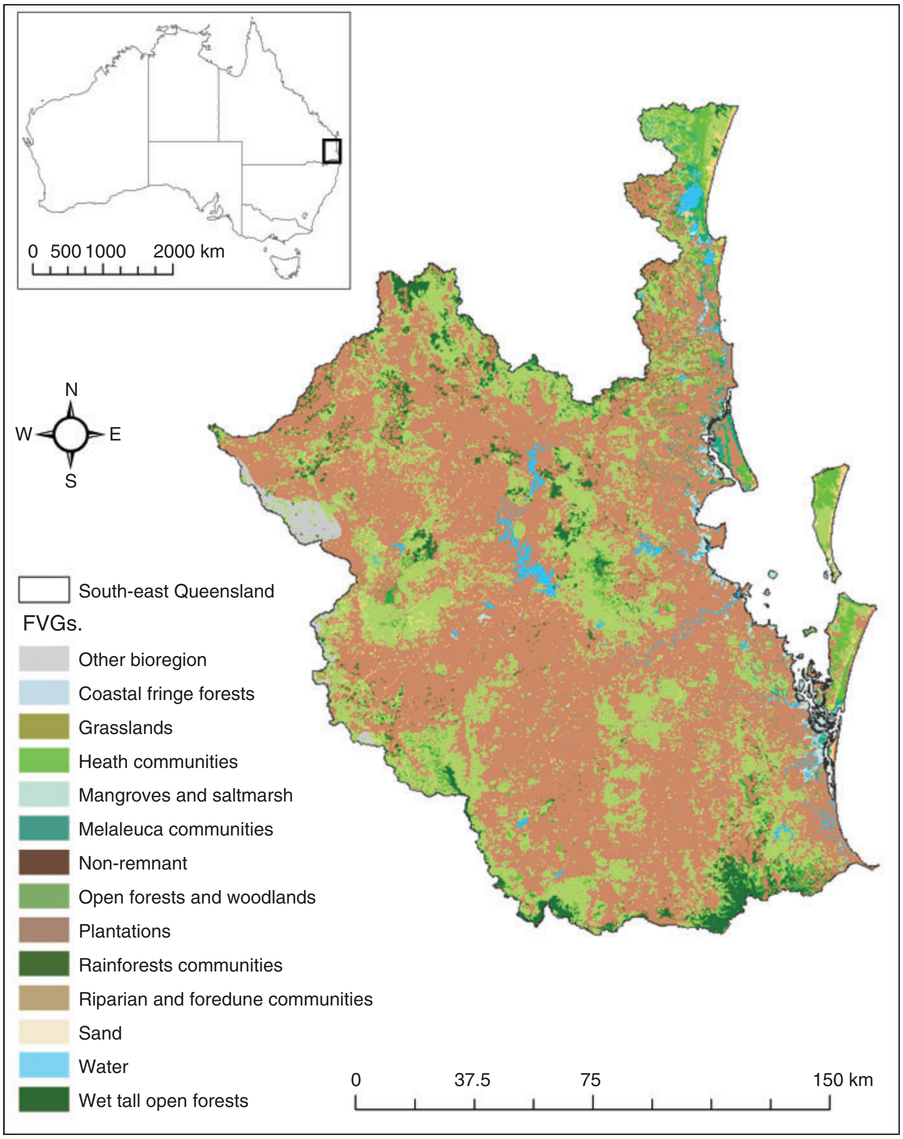

Fig. 1. South-east Queensland study area representing the water catchment of the area and the simplified Fire Vegetation Groups (FVG) (Neldner *et al.* 2017*a*, 2017*b*). Source: Biodiversity status of 2017 remnant regional ecosystems – Queensland, Queensland Spatial Catalogue (Queensland Government).

they occur. The present study aimed to describe and improve our understanding of fire regimes on public land, using SEQ as a case study area, based on existing fire records. We also aimed to determine whether: (1) different aspects of the fire regime (frequency, season and extent) differ between planned and unplanned fire; (2) different broad fire vegetation groups (FVGs) are more likely to be subject to planned or unplanned fires; and (3) there are relationships between rainfall and planned and unplanned fire extents. Mapping of the fire regime for regions like SEQ will lead to improved fire management through identification of areas that have not burnt for some time and therefore represent a higher wildfire risk, or are in urgent need of burning (or fire exclusion) to sustain populations of species sensitive to inappropriate fire regimes.

Materials and methods

Study area

The present study used the catchment area for SEQ. The area extends to the southern section of the Great Sandy National Park (Noosa North Shore) in the north, the New South Wales border in the south and Yarraman and Toowoomba in the west (Fig. 1). The acronym SEQ is used in this manuscript to denote the study region. The SEQ catchment area has a mostly subtropical climate and covers an area of ~2 352 500 ha. Mean annual rainfall in the region ranges from 1000 to 2000 mm, with higher rainfall recorded close to the east coast and lower rainfall recorded in the western parts of the study area (http://www.bom.gov.au/climate/data, accessed July 2019). Rainfall is lowest from late

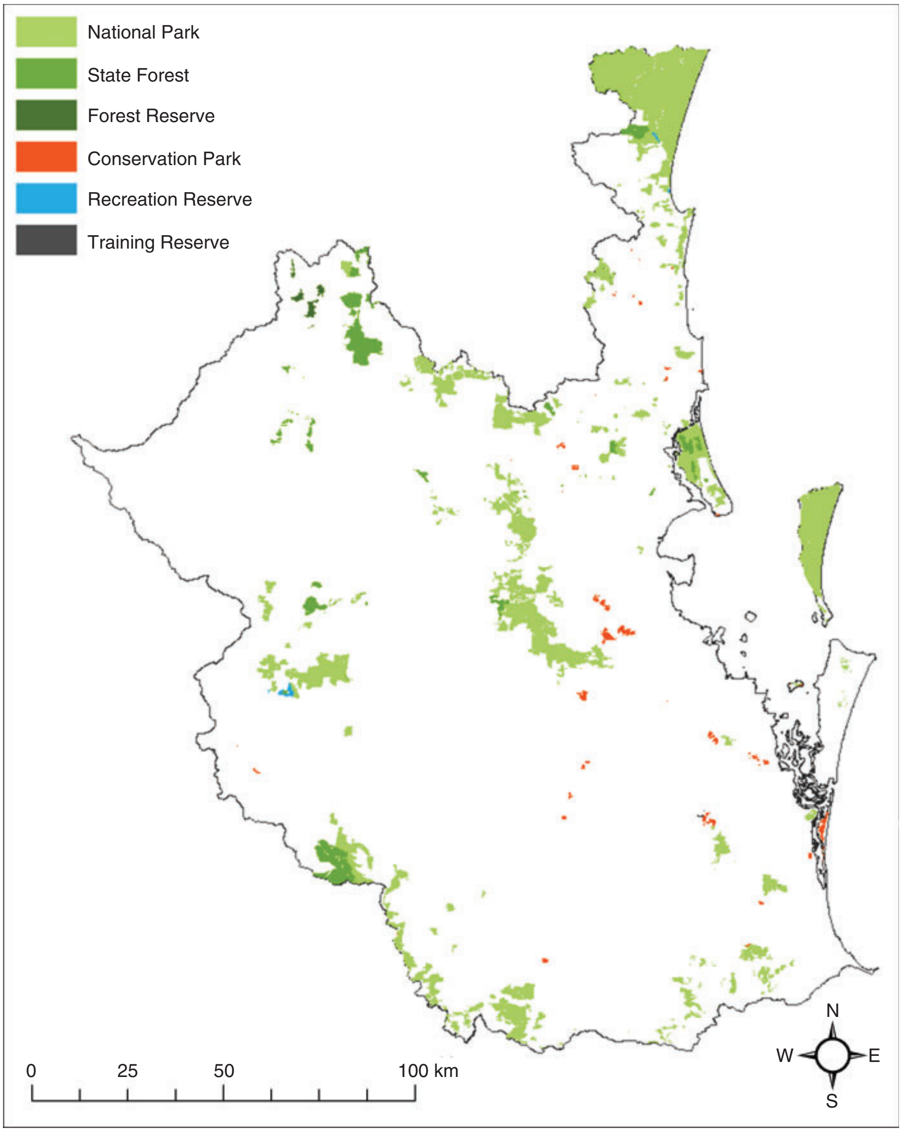

Fig. 2. State-Government-managed public land in south-east Queensland.

spring (October) to early summer (December), with highest rainfall usually in the summer months (December to February). Mean maximum temperatures during summer range from 27 to 36°C, and for winter the mean maximum temperature range is between 15 and 21°C (http://www.bom.gov.au/climate/data). Coastal areas usually record lower maximum temperatures than the western areas.

There are many different vegetation types in the study area (Fig. 1). The Queensland Herbarium has developed detailed descriptions of structure and floristic composition for 'regional ecosystems' in Queensland (Neldner and Accad 2015; Neldner *et al.* 2017*a*). This includes a simplified set of FVGs, which have been utilised in the present study (Fig. 1). Additionally, there are areas of plantations (mostly introduced *Pinus* species) that are sometimes adjacent to QPWS-managed land. These plantations are managed by HQ Plantations (HQPlantations 2014), who undertake their own fuel management, including planned burns. However, burns carried out by HQ Plantations were not included in the present study, unless plantation areas were burnt during unplanned fires or where plantations were adjacent to QPWS-managed land.

Archived fire reports

Archived burn report data, obtained from QPWS and predecessor resource management agencies, were analysed to determine recent fire regimes for the study region on state-government-managed public land. State-government-managed land covers ~9% of the total SEQ study area. This includes national park (84%), state forests (12%), recreation reserves (0.4%), training reserves (0.03%), forest reserves (0.9%) and conservation parks (2.7%) (Fig. 2). Some of the fire report information was inaccurate or partially missing up until the early 2000s, and for this reason, analysis has only been conducted on data between 2004 and 2015. The fire report data for SEQ were

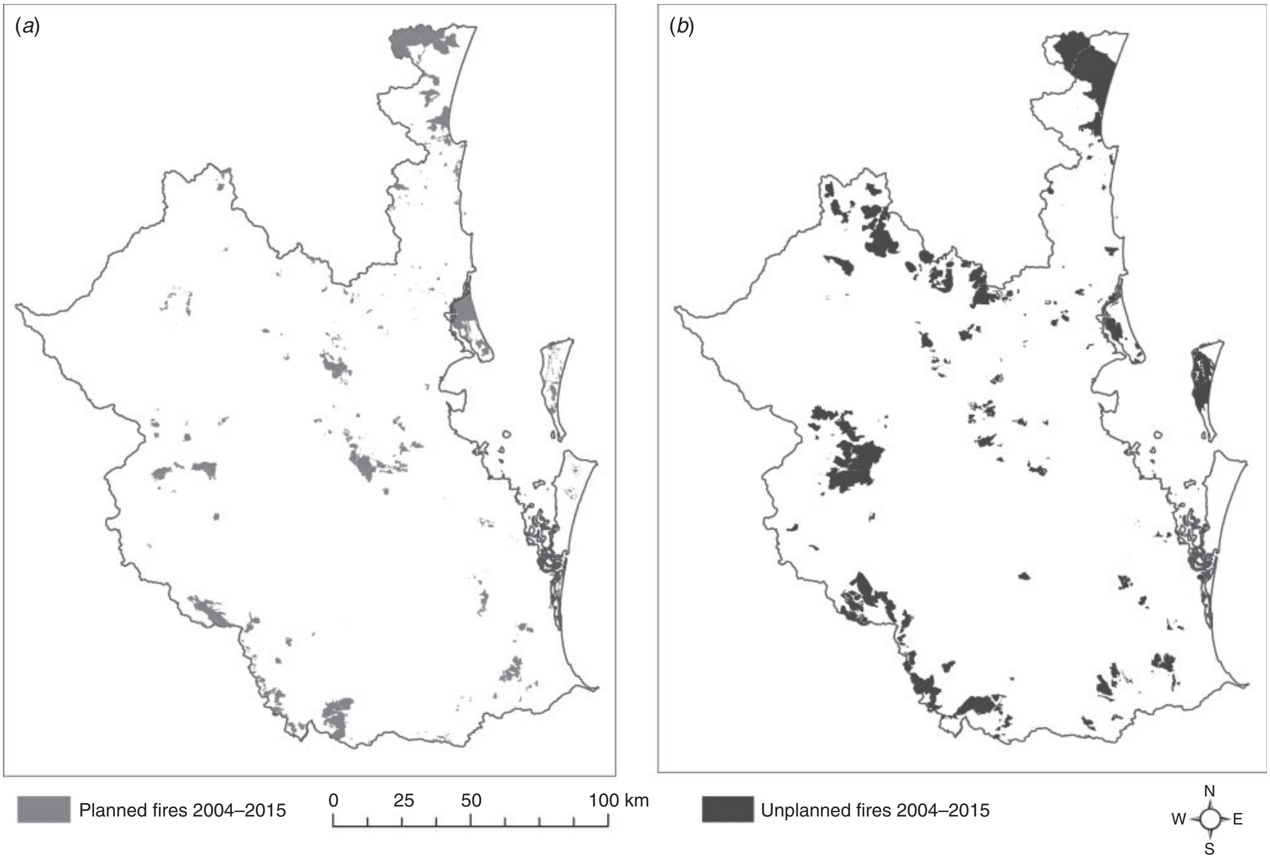

Fig. 3. Cumulative burnt areas from (*a*) planned fire and (*b*) unplanned fire in south-east Queensland, from Queensland Parks and Wildlife Service fire reports between 2004 and 2015.

in the form of digitised Geographic Information System (GIS) maps developed from burnt area boundaries based on field assessment, and included various attributes. There were 1227 known fire events recorded between 2004 and 2015, and each was identified as either a 'planned burn' or 'unplanned burn' (Fig. 3). The present study focused on the spatial distribution of each fire and the temporal variation using the date of each fire and ArcGIS 10.6 software (ESRI 2018, Environmental Systems Research Institute, Redlands, CA, USA).

Spatial and temporal analysis

Using the archived fire reports from QPWS, basic raster-based analytic procedures contained in ArcGIS and a proven method of analysis (Srivastava *et al.* 2013), we assessed the spatial and temporal variation in fire frequency, extent and season. In this analysis we were unable to incorporate fire intensity as a result of a lack of data on this component of the fire regime. Srivastava *et al.* (2013) used individual fire events between the years 2004 and 2015, compiled as individual polygons to represent a manually mapped burnt area perimeter. These polygons were converted to a raster format, cell resolution of 30 m, to derive a variety of descriptive fire regime parameters for comparison using the ArcGIS 10.6 software. This method was used here because, for analysis purposes, the data are in a simpler format that is more efficient for use in raster analysis, rather than other types of analyses with ArcGIS. As there were no historic data collected on fire intensity in the burn reports, we were not able to analyse this component of the fire regime. Prior to the analysis, the dataset were organised as a spatial layer, and new attribute fields such as burnt area, year of fire, month of fire, season of fire and burn date were created.

For calculating fire extent, the spatial data were split into separate polygons for each year, and these polygons representing yearly burn were further split according to burn type (planned and unplanned burns). This analysis provided spatial layers for 12 separate years over the period between 2004 and 2015. Thereafter, each polygon was converted into raster format with information on burnt area for each year and burn type (pixel value 1 = burnt, pixel value 0 = unburnt). This enabled calculation of the total burnt area (calculated by multiplying number of pixels by the pixel size (900 m^2)) for each year and for the two burn types (i.e. planned and unplanned burns).

For fire frequency the data were split into separate polygons using the existing field of burn type (planned and unplanned burns), and then each day a fire event occurred. Thereafter, each fire event date polygon was converted into a raster dataset using the burnt field to assign the raster value. All the individual raster burn date datasets were summed together to derive the overall fire frequency for planned and unplanned burns.

To analyse the season in which fire occurred, the data were split into separate polygons for each fire season, and again for the existing field of burn type. Each polygon was converted into raster format using the burnt field to give a raster file of burnt area for each season and burn type, creating raster datasets for each season and burn type.

To incorporate vegetation types into the analysis, the Regional Ecosystem (RE) dataset was used. The RE dataset is managed by the Queensland Herbarium, which is a branch of the Queensland Department of Science and Environment. The RE dataset is a map of vegetation that has been collected by a variety of methods and includes vegetation communities associated within a regional ecosystem that have similar structure and floristics occurring in the same land zone (Neldner *et al.* 2017*a*; Neldner *et al.* 2019). Within the RE dataset are Broad Vegetation Groups (BVGs), which are a higher-level grouping of vegetation communities, and also include broad FVGs, which were used in this research (Neldner *et al.* 2017*a*, 2017*b*). To classify the FVG groups, floristic, structural, functional, biogeographic and landscape attributes are used. The aggregations of the FVGs are determined on the basis of vegetation structure (cover, height and growth form) of the ecologically dominant layer, and those not dominated by trees or tall shrubs (Neldner *et al.* 2017*a*, 2017*b*).

The FVG dataset was clipped to give the FVGs for the same area of the fire report data. Both the fire report data and the FVG data were converted into raster data. For the FVG data, the FVG field was used to give the number of pixels for each of the FVG types. Following this, a 'combinatorial raster operation' was performed to calculate the area for each FVG as well as planned and unplanned burn. For analysis purposes, the unrelated FVG groups and groups that had very low records of fire were excluded (i.e. coastal fringing forests and headlands, grassland, mangroves and saltmarsh, sand, water and unclassified areas). Additionally, the FVG areas do not change in size over the study period, whereas the burnt areas vary annually and are cumulative over the study period, which needs to be taken into account when comparing burnt areas of the FVGs across years.

Because rainfall has an important influence on fuel moisture and fuel load (Price and Bradstock 2011; Sullivan *et al.* 2012; Storey *et al.* 2016), historic (and interpolated) rainfall data were accessed and used to investigate relationships with planned and unplanned burn extents. First, the monthly rainfall for each of the 12 years over the study period were downloaded as NetCDF files (https://silo.longpaddock.qld.gov.au/silo/gridded-data/, accessed 6 August 2019). The files were converted into a raster layer for each month using ArcGIS, and the dataset was extracted for the SEQ region. The rainfall data for each unplanned and planned burnt area were extracted in a tabular form. The rainfall information was summarised to calculate monthly average rainfall using ArcGIS. The annual rainfall was recorded as the sum of the mean monthly rainfall. The mean monthly rainfall and the associated monthly extent for planned and unplanned burns were further analysed in IBM SPSS Statistics for Windows, Version 24.0 (IBM Corp., Armonk, NY, USA) to test for relationships between rainfall (monthly, annual and seasonal) and planned and unplanned burn extents, using Pearson's correlation and simple linear regression. This indicated the extent to which any variables were related and what the relationship was between the variables.

Table 2. Total annual fire extent for all fire, planned fire and unplanned fire within the study region in the 2004–15 period

Area (ha) values for total, planned and unplanned fires and percentage (%) in parenthesis for planned and unplanned fire in each year

Year	Total	Planned	Unplanned
2004	36 445	9568 (26.3)	26 899 (73.8)
2005	28 261	2984 (10.6)	25 278 (89.4)
2006	24 372	3645 (15.0)	20 864 (85.6)
2007	16 508	5921 (35.9)	10 587 (64.1)
2008	8532	3016 (35.4)	5516 (64.6)
2009	66 624	7684 (11.5)	59 000 (88.6)
2010	9102	9055 (99.5)	47 (0.5)
2011	28 928	12 030 (41.6)	16 995 (58.7)
2012	50 533	9346 (18.5)	41 242 (81.6)
2013	33 889	19 525 (57.6)	14 365 (42.4)
2014	18 373	12 291 (66.9)	6625 (36.1)
2015	13 432	10 039 (74.7)	3392 (25.3)
Total	335 000	105 105 (31.4)	230 811 (68.6)
Mean annual burn area	27 917	8759	19 234
s.e.	4994	1358	4949

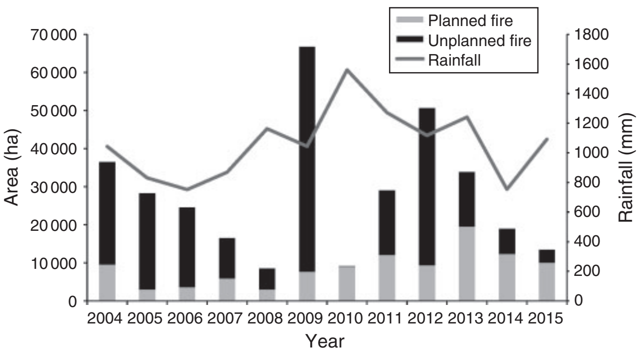

Fig. 4. Fire extent (ha) for planned fire and unplanned fire within the study region, and mean annual rainfall.

Results

Extent

The total area burnt between 2004 and 2015 was 339 479 ha, with planned burns covering a cumulative 31.4%, and unplanned fire 68.6% (Table 2; Fig. 3). Spatial and temporal analysis revealed large fluctuations in the area burnt in a given year (Fig. 4). Mean annual area burnt by planned burns was significantly lower than that burnt by unplanned fire (t (d.f. = 13) = −2.04, P = 0.03). Total area burnt gradually decreased from 2004 to 2008, with unplanned fire accounting for the majority of area burnt (Table 2; Fig. 4). In 2009, the total area burnt was greater than in any other year during the period of the present study, with unplanned fire accounting for most area burnt. There was a total of 68 unplanned fires in 2009, including six large unplanned fires in spring, one very large unplanned fire in spring (19 539 ha) and two large unplanned fires at the end of winter (6452 ha). Unplanned fire extent in November 2009 accounted for 54.3% of the total unplanned fire extent that year. Following this, there was a large decrease in area burnt in 2010, and planned burns accounted for most of area burnt. In 2011, there was an increase in area burnt again; however, unplanned fire and planned fires covered similar annual burn areas. There was a continued increase in area burnt in 2012 (50 533 ha), with unplanned fire again accounting for the majority of area burnt. There was a gradual decrease in total area burnt from 2013 to 2015. During this period the majority of area was burnt by planned burns, with 2013 having the largest planned burn area during the study period. In relation to QPWS meeting annual targets of burning 5% of the total QPWS-managed pubic land in SEQ, the planned burn targets were reached in 2010–15, but not in 2005–09.

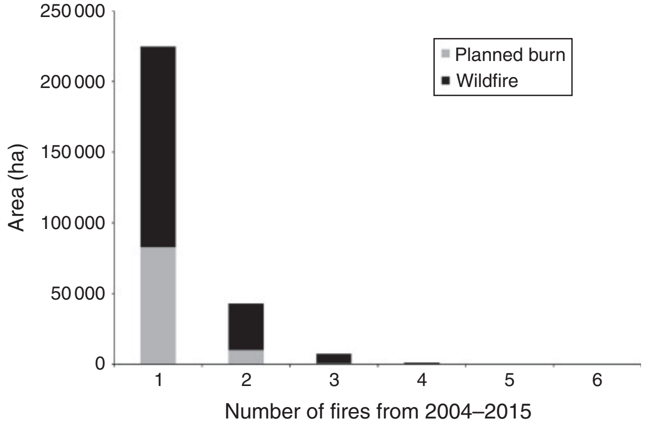

Fig. 5. Area burnt (ha) under different fire frequencies. The number of fire events between 2004 and 2015 for the study area was based on the number of times a pixel was burnt during the study period.

Frequency

In total, 82 844 ha were burnt once with planned fire over the 12-year period, and 141 822 ha were burnt once by unplanned fire over the same period (Figs 5, 6). Areas burnt twice over the 12-year period covered 10 012 ha for planned burns and 32 894 ha for unplanned fire. Smaller areas were burnt three times over the 12 years; planned burns accounted for 671 ha and unplanned fire 6742 ha. Much smaller areas were burnt more

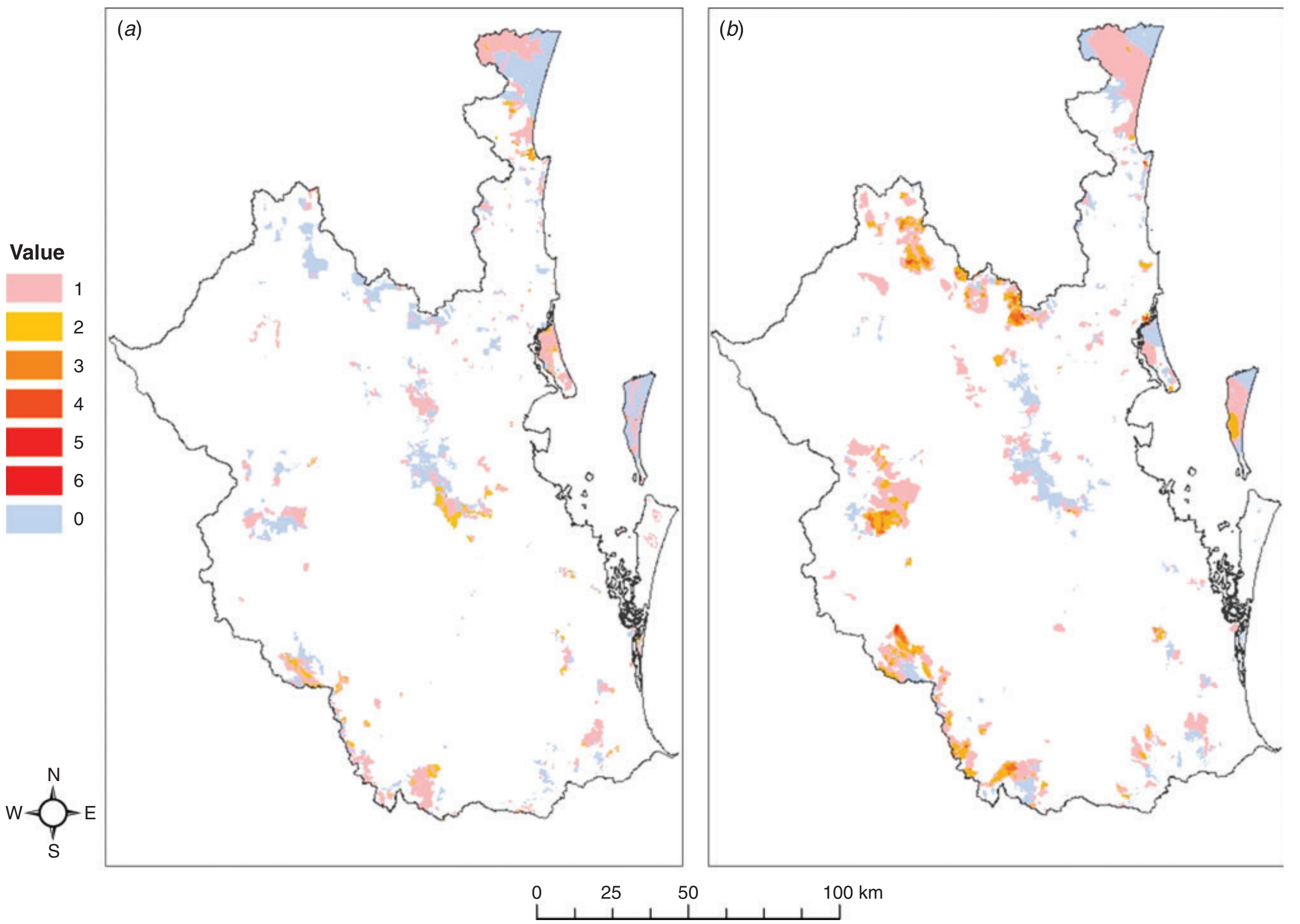

Fig. 6. The number of fire events between 2004 and 2015 for the study area. With (*a*) planned burn area and (*b*) unplanned burn area. Values in the legend represent the number of fires.

than four times (Fig. 5), and no areas were burnt by either fire type more than six times during the 12-year period. Out of all of the QPWS-managed land, 48 754 ha (23.8%) were not burnt during the study period.

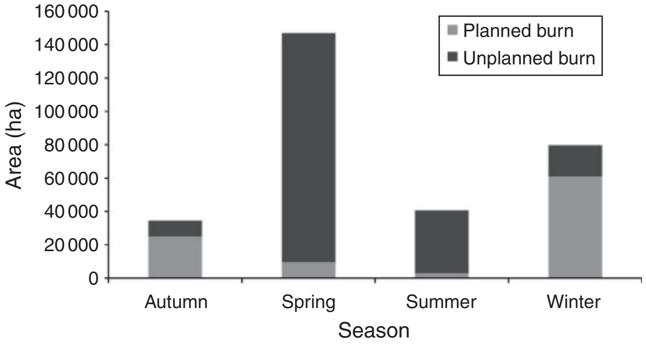

Fig. 7. Area of planned burns and unplanned burns in different seasons within the study region between 2004 and 2015.

Season

Most fire in the study region occurred in spring (144 753 ha), with unplanned fire accounting for the majority of the burnt area (94.6%) (Figs 7, 8*a*, *b*). Winter recorded the second largest burnt area (78 744 ha), with planned burning accounting for the majority of burnt area (77.6%) (Figs 7, 8*c*, *d*). Autumn and summer had similar burnt areas (33 044 ha and 40 445 ha respectively), with planned burns accounting for the majority of burnt area in autumn (76.2%), and unplanned fires accounting for most of the burnt area in summer (92.8%).

Fire vegetation groups

The areas covered by each FVG in the study area, in order of decreasing total area are: open forests and woodlands (201 402 ha); non-remnant (49 019 ha); heath communities (26 208 ha); melaleuca communities (15 332 ha); rainforests and brigalow communities (12 365 ha); riparian communities (10 393 ha); wet tall open forests (9398 ha); and plantations (4799 ha). Between 2004 and 2015, there was clearly more fire (planned and unplanned) in open forests and woodlands than in

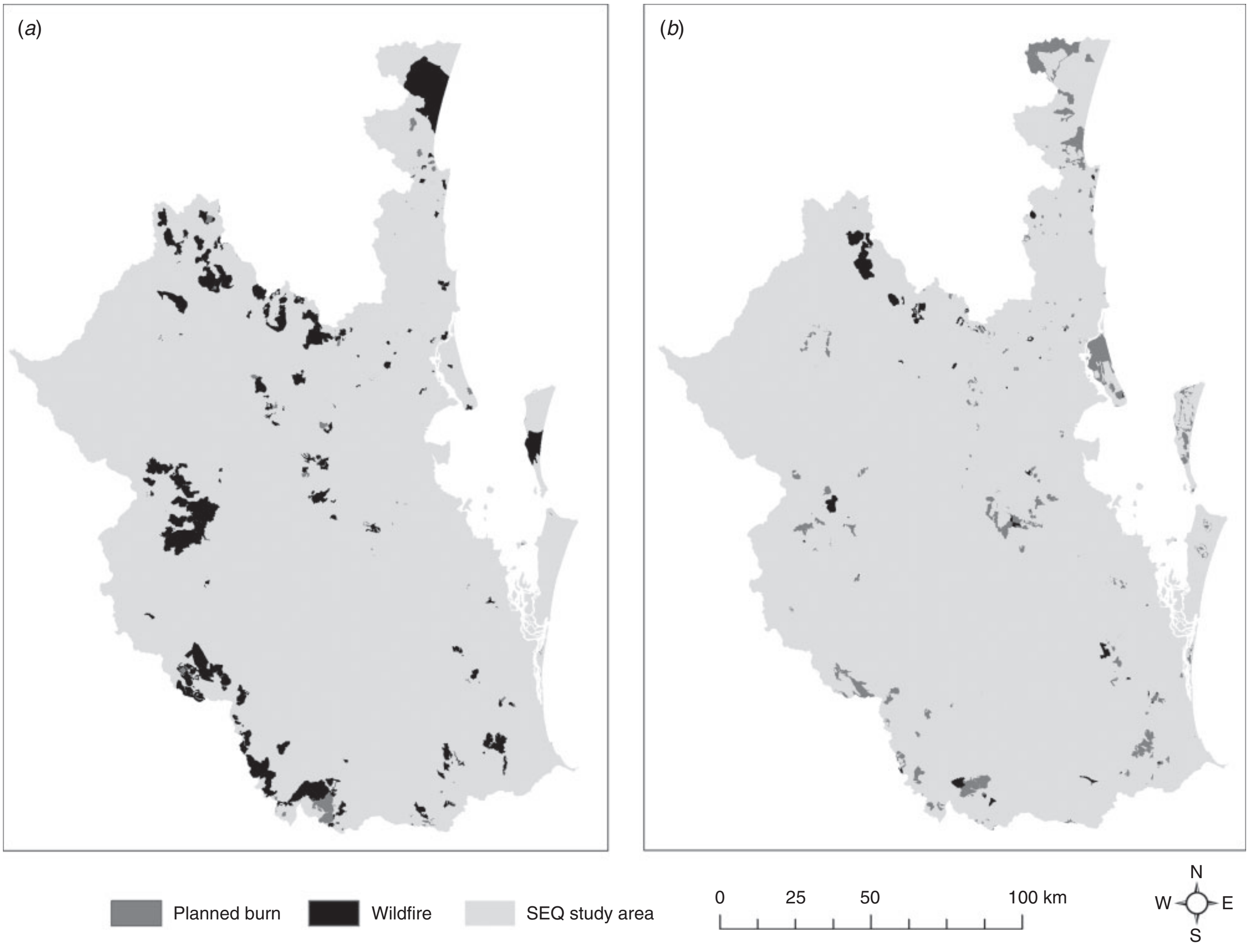

Fig. 8. Planned burn and unplanned burn areas for the two seasons that recorded the most burnt area between 2004 and 2015. Map (*a*) represents spring planned and unplanned burns, and (*b*) represents winter planned and unplanned burns. SEQ, south-east Queensland.

Table 3. Total fire vegetation group fire extent for all fire, planned fire and unplanned fire within the study region in the 2004–15 period
Area (ha) values for total, planned and unplanned fires and percentage (%) in parenthesis for planned and unplanned fire in each fire vegetation group (FVG)

FVG	Total	Planned	Unplanned	Planned percentage of total FVG area	Unplanned percentage of total FVG area
Heath communities	26 208	7083 (32.6)	14 674 (67.4)	27.0	56.0
Melaleuca communities	15 332	8017 (58.8)	5615 (41.2)	52.3	36.6
Riparian, foredune, coral cay island and beach ridge communities	10 393	1707 (24.7)	5217 (75.3)	16.4	50.2
Open forests and woodlands	201 402	42 457 (28.6)	106 106 (71.4)	21.1	52.7
Rainforests, dry vine forests and brigalow communities	12 365	1228 (17.2)	5927 (82.8)	9.9	47.9
Wet tall open forests	9398	1480 (28.0)	3812 (72.0)	15.8	40.6
Non-remnant	49 019	3573 (10.9)	29 142 (89.1)	7.3	59.5
Plantations	4799	2443 (66.6)	1223 (33.4)	50.9	25.5

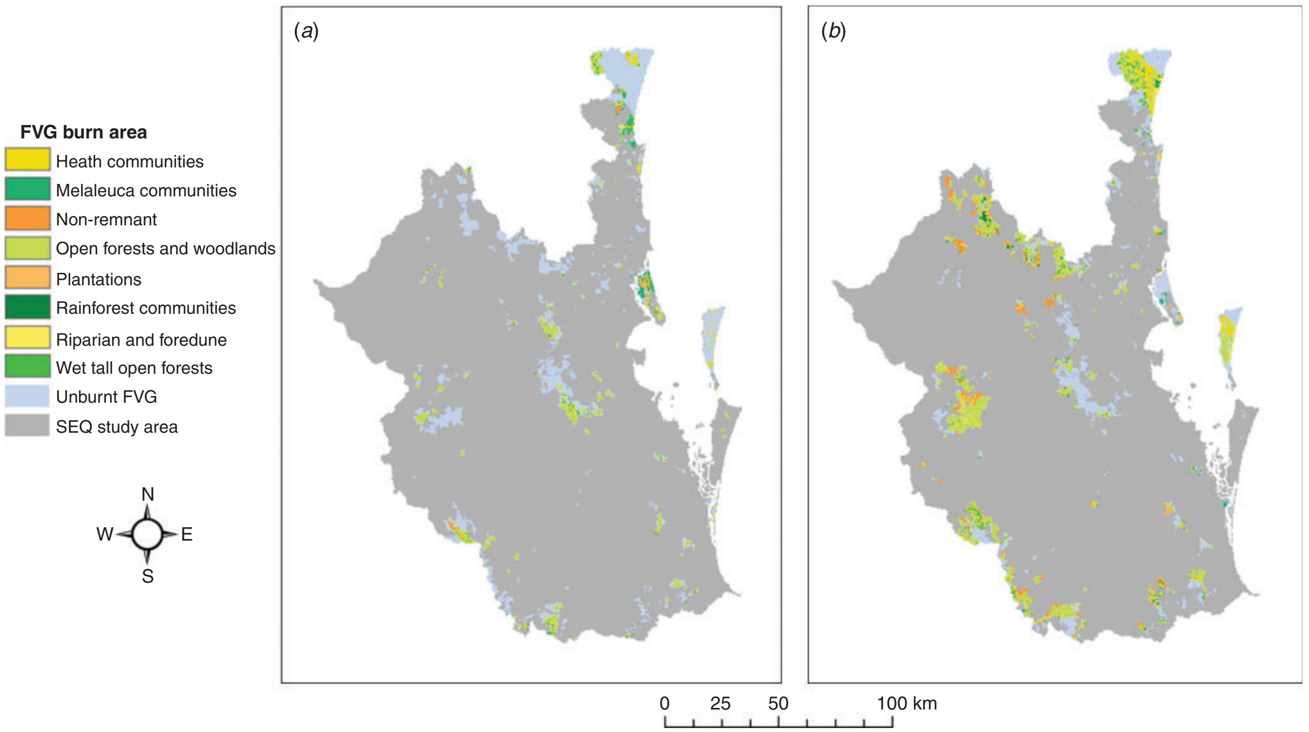

Fig. 9. Spatial representation of the fire vegetation groups (FVG) for (*a*) planned fire and (*b*) unplanned fire between 2004 and 2015. SEQ, south-east Queensland.

other vegetation types in SEQ (Table 3; Fig. 9). Of the total area burnt in open forests and woodlands, unplanned fire accounted for 71.4% of the area burnt, and 50.2% of the total open forest and woodlands area was burnt by unplanned fire over the study period. Planned burns accounted for 28.6% of area burnt and only covered 21.1% of the area of this vegetation type. Non-remnant vegetation recorded the second highest burn area (32 716 ha out of a total vegetation-type area of 49 019 ha). The majority was burnt by unplanned fire, which covered 59.5% of the area of this vegetation type; planned burns covered only 7.3%. Heath communities (21 756 ha burnt out of a total vegetation-type area of 26 208 ha) were also mostly burnt by unplanned fire (67.4%), which was half of the total heath community's area, and planned burns (32.6%) covered 27.0% of the total heathland vegetation-type area. The other five FVGs covered relatively small areas of the QPWS-managed area and had lower burn extents. In order from highest to lowest burn area: melaleuca communities (13 632 ha out of a total of 15 332 ha, planned burn 58.8%); rainforests, dry vine forests and brigalow communities (7155 ha out of a total of 12365 ha, unplanned fire 82.8%); riparian, foredune, coral cay island and beach ridge communities (6924 ha out of a total of 10 393 ha, unplanned fire 75.3%); wet tall open forests (5292 ha out of a total of 9397 ha, unplanned fire 72.0%); and plantations (3666 ha out of a total of 4799 ha, planned burn 66.6%).

Rainfall

Mean annual rainfall calculated for the region varied among years during the study period (Fig. 4). A significant relationship was detected between mean annual rainfall and planned burn extent (r ($n = 143$) $= -0.30$, $P < 0.001$). A linear regression model with season and rainfall explained 38% of the variation in unplanned fire extent in the time frame of our study ($F_{7,40} = 5.1$, $P < 0.001$). The area affected by unplanned fire was significantly larger in spring (29 995 ha $\pm$ 5483, t (d.f. $= 40$) $= 5.5$, $P < 0.001$) than in other seasons of the year (estimates ranging from 1961 ha in winter to 5195 ha in summer), and there was a negative relationship between spring rainfall and unplanned fire extent (slope $= -75.1 \pm 23.5$, t (d.f. $= 40$) $= -3.2$, $P = 0.003$).

Discussion

Unplanned fires covered a greater extent than planned burns in the region. However, the extent of planned fire was greater than that of unplanned fire in some years (i.e. 2010, 2013, 2014 and 2015). Of the 339 479 ha of QPWS-managed estate burnt between 2004 and 2015, more than two-thirds of the fire extent was burnt by unplanned fire. This is important to know because unplanned fires usually burn at a higher intensity and occur during drier conditions than planned fires, and differences in fire intensity may have significant ecological ramifications, resulting is modifications to an ecosystem (e.g. influencing plant regeneration) (Gosper *et al.* 2013; Chick *et al.* 2018; Eliott *et al.* 2019).

There was significant variation in the extent of fire among years, which was in part related to rainfall patterns; rainfall influenced unplanned fire extent during all seasons, particularly in spring. For example, unplanned fire extent was particularly high in 2009, and this appeared to be related to the high rainfall recorded during the wet season (2008–09), followed by a dry spring in that year. Such conditions would have resulted in accumulation of a high fuel load before the spring, when most unplanned fires occurred in that year. During 2010, most of the area burnt was from planned burns, and very small areas were affected by unplanned fire. The increase in burnt area over the next 3 years (2011 to 2013) was partly due to the increase in planned burning by QPWS in 2013, but was also likely related to fuel accumulation, because of the high rainfall events experienced in the region during the same time.

Contrary to our expectation, unplanned fires occurred more frequently than planned fires across the SEQ landscape. A large area (48 754 ha, 23.8%) was not subject to any fire over the 12-year period of the present study and large areas were also influenced by a single fire (either planned or unplanned fire). However, only relatively small areas received more than one planned fire in the 12-year period. With fire management agencies battling a warming climate (and potentially shorter periods of opportunity for planned burns), and being restricted by annual budgets for planned burns, it is a challenge to ensure planned burning targets are met for the different vegetation types.

Between 2004 and 2015, the majority of planned burning occurred during winter and autumn, and the majority of unplanned fires occurred during spring and summer. This follows our expectations based on fire weather conditions (Gill *et al.* 2012; Queensland Parks and Wildlife Service 2012; South-east Queensland Fire and Biodiversity Consortium 2014). Under a more variable climate, the fire season in the region can easily extend into early summer (before significant rainfall events occur), leading to an increased risk of potentially damaging unplanned fire (Storey *et al.* 2016; Lydersen *et al.* 2017).

The majority of all fires (planned and unplanned) occurred in open forests and woodlands. This is to be expected owing to the large extent of this vegetation type in the region and the flammable nature of eucalypt forests and woodlands (Queensland Herbarium 2016; Neldner *et al.* 2017*a*). Heathland communities were also common in the study region and were frequently subject to unplanned fire; these vegetation types are also known to be particularly flammable (Gill 1979; Myerscough and Clarke 2007; Plucinski *et al.* 2017). Because heath communities, as well as open forest and woodlands, are frequently burnt by unplanned fire in the region, there may be less emphasis on planned burning in these vegetation types to ensure appropriate fire frequencies are maintained. However, fire managers should not use this as a reason to not apply planned fire in such areas, where planned burning is often the best way to break the cycle of re-occurring wildfires (e.g. through modifications in the fuel structure). Planned burns in certain ecosystems (e.g. heathlands and wet tall open forests) can be difficult to achieve, as a result of the narrow window of opportunity in suitable weather conditions to carry out the planned burn safely (Queensland Parks and Wildlife Service 2012; Penman *et al.* 2013; Storey *et al.* 2016).

Our findings suggest that if periods of high rainfall are followed by periods of dry conditions, there is an increased risk of unplanned fire, specifically during the fire season. This is also likely the case in other regions in Australia, despite fire seasons occurring at different times of the year compared with SEQ (Sharples *et al.* 2016; Ndalila *et al.* 2018). Additionally, high rainfall during the fire season may lead to a decrease in unplanned fire, and can decrease the length of the fire season. This suggests that for planned fire management, increased rainfall periods and associated higher fuel moisture contents can dramatically affect the operational planned burn targets of management agencies. This can lead to a situation where only the highest priority planned burns are undertaken during the shortened planned fire season.

With the data available, it is challenging to identify whether QPWS is meeting ecological thresholds during planned burn activities. For example, it is difficult to accurately determine whether areas have been burnt within their recommended interval due to the short period of data collection here. However, a general indication regarding ecological requirements is possible, with large areas (26.2%) of eucalypt forest not burnt in the 12 years covered by the present study, suggesting bias towards the longer unburnt end of fire guidelines. Continued collection of fire history data is important for assessing fire frequency across different ecosystems. Additionally, fire season guidelines are often not being met, with common and widespread eucalypt forests having a recommended fire season of summer to winter, yet most unplanned fires occur in spring.

With the focus of planned burns by QPWS on protection, wildfire mitigation and fuel management (i.e. 85% in 2017), ecological burns at times and conditions appropriate for local flora and fauna become less common, particularly when budgets for planned burning are restricted. There also needs to be consideration that QPWS burning programs are not fixed targets, but more a guideline to provide best overall outcomes within resourcing and burn weather constraints (P. Leeson, pers. comm. 21 November 2018).

In Australia, Western Australia (WA) and Victoria also have annual planned burn targets; however, information on whether they have met these targets is sometimes not publicly available. In the 2016–17 reporting year, the WA Department of Parks and Wildlife (DPAW) achieved 247 360 ha of prescribed burning in the south-west forest regions, and an additional 2 988 394 ha from extra Government funding (Department of Parks and Wildlife 2017). If there were no extra funding that year, it would have reduced the amount of planned burning the DPAW were able to accomplish. In Victoria, the Department of Environment, Land, Water and Planning (DELWP) is responsible for managing unplanned risk on public land, and has fire management zones that have a recommended tolerable fire interval for different vegetation types (Department of Environment, Land Water and Planning 2017). The DELWP had similar variations in the amount of planned burning as that conducted by QPWS in the present study. In the 2016–17 reporting year, the DELWP completed 49% of its proposed planned burning, with 92.6% and 72.9% of its target planned burns in the preceding years, and in some other years, >100% of target burns completed. The USA has planned burn targets similar to Australia's, to assist in the reduction in unplanned fire risk, but again, the actual targets and the results from planned burn implementation are not readily available. US Forest Service fuel-reduction treatments have been proven to work, with assessments of 3700 fuel treatments since 2006 showing that they are effective in reducing wildfire severity and helping to control wildfires (United States Department of Agriculture Forest Service 2018). However, the majority of area burnt annually on US Forest Service land is the result of unplanned fire, and in 2017 ~1.17 million hectares burned across National Forest System lands, a 92% increase compared with the 10-year average of 0.61 million ha (United States Department of Agriculture Forest Service 2018). Although there are specific intentions of planned burn programs, it is inevitable that unplanned fire extent will be high in certain years, when conditions encourage unplanned fire spread across the landscape.

In regards to our case study in SEQ, although QPWS planned burn targets were for the entire state of Queensland, it is important to point out that larger areas of northern Queensland (e.g. tropical savannas) burn more frequently relative to the remainder of the state (Andersen *et al.* 1998; Preece 2007; Penman *et al.* 2011). Additionally, although there are similar goals for planned burning in SEQ compared with other jurisdictions, there are still differences in the targets and funding support from governments. Individual regions in Australia and elsewhere ideally require specific targets and funding, owing to the heterogeneity across landscapes (i.e. variation in vegetation types, proximity to human settlements etc.) and across years. In the present study, we have identified that QPWS reaches its annual planned burn target some years, and in the years they do not, this failure is related to unfavourable planned burn conditions and the transition from the fire season to the wet season. From the extent analysis in the present study, we identified low numbers of planned burn areas before 2009, and higher numbers of planned burn areas following 2009. This could be due to the Commonwealth Government's planned burn policy change following the Victorian Black Saturday fires, which also occurred in 2009. Overall, between 2004 and 2015, the results suggest that QPWS did not reach its annual planned burn targets during most years in SEQ.

There are some matters that need to be taken into consideration in regards to the accuracy of this analysis. First, because there were conversions of fire event polygons to raster format, there was simplification of the boundaries – raster format is set out as pixels, which sometimes do not follow the same line as the vector format polygons. However, as this process was completed on all of the data, the generalisations would be consistent throughout the analyses; some overestimates would have been cancelled out by underestimates, and the magnitude of error was low as a result of the spatial resolution and scale of the raster files fitting within the scale of the original dataset. Second, during the frequency analysis, on an individual day (date) that fire was recorded, if there was a repeated record of a fire or if, for whatever reasons, a plan burn escaped to become an unplanned burn and recorded twice at the same location, only one fire was reported in the analysis. Third, this assessment is based on maps that have been hand drawn by QPWS, and these maps can sometimes be inadequate (Srivastava *et al.* 2013), which is why we used fire reports post 2004. There are many new technologies available currently that can accurately map burnt areas, such as satellite images, remote sensing and multi-spectral data (SK Srivastava, T Lewis, L Behredorff and S Phinn. unpubl. data; Alonso-Canas and Chuvieco 2015; Humber *et al.* 2019). QPWS should consider such technologies to monitor the effectiveness of its planned burn management programs, although further work is required at a local scale to verify these technologies. Finally, the FVGs, which are based on the Regional Ecosystem dataset, has a degree of inaccuracy, despite a vigorous process of independently collecting quantitative data that has been validated to achieve a reliable set of data (Neldner *et al.* 2017*a*, 2017*b*).

The present study demonstrates the importance of accurately recording and storing fire occurrence data, including spatial distributions of fire to allow mapping of fire regime. Further collation of such data is needed to allow future analysis over a longer time period than the 12 years in the present study. This would then allow investigation of fire frequencies in different regions and vegetation types over longer time periods, to ensure that management recommendations are adhered to. Fire regime mapping is a valuable tool for management agencies to identify priority areas for planned burning. Although the focus of the present study has been on publicly managed land, private land owners with vegetation groups similar to those described in the present study can also benefit from efficient, accurate recording and collection of fire occurrence data. Recording of fire events by private landowners themselves would help support the management of their own land with fire, whether it be for ecological purposes, risk to their valued assets or both.

Conclusion

Overall, in the present study, planned burns and unplanned regimes differed in terms of fire extent, season and frequency on

QPWS-managed land between 2004 and 2015. Our analysis of the fire regimes within SEQ clearly shows that there has been much more area burnt by unplanned fire than planned fire on the landscape. The impacts of unplanned fire relative to planned burning requires further investigation across different vegetation types in the region. Nevertheless, previous studies (e.g. Attiwill and Adams 2013; Gill *et al.* 2013) generally report more negative effects of unplanned fires, as a result of their generally higher intensity and degree of burn coverage. While governments acknowledge and support the use of planned fire, there are still limited resources available for government agencies to ensure an appropriate level of planned burning to achieve not only risk-reduction objectives, but also ecological objectives. In light of this, spatial mapping can inform and assist in the adaptive management required by public land managers, and continuing fire-related data collection and analysis can support fire management operations.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

We acknowledge the University of the Sunshine Coast for funding the PhD of the lead author. We would also like to thank Queensland Parks and Wildlife Service, in particular, Peter Leeson, for providing information on their fire management procedures and supplying historical burn data for the study area.

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