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Severe and Short Interval Fires Rearrange Dry Forest Fuel Arrays in South-Eastern Australia

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Abstract: Fire regimes have shaped extant vegetation communities, and subsequently fuel arrays, in fire-prone landscapes. Understanding how resilient fuel arrays are to fire regime attributes will be key for future fire management actions, given global fire regime shifts. We use a network of 63-field sites across the Sydney Basin Bioregion (Australia) to quantify how fire interval (short: last three fires <10 years apart, long: last two fires >10 years apart) and severity (low: understorey canopy scorched, high: understorey and overstorey canopy scorched), impacted fuel attribute values 2.5 years after Australia's 2019–2020 Black Summer fires. Tree bark fuel hazard, herbaceous (near-surface fuels; grasses, sedges <50 cm height) fuel hazard, and ground litter (surface fuels) fuel cover and load were higher in areas burned by low- rather than high-severity fire. Conversely, midstorey (elevated fuels: shrubs, trees 50 cm–200 m in height) fuel cover and hazard were higher in areas burned by high- rather than low-severity fire. Elevated fuel cover, vertical connectivity, height and fuel hazard were also higher at long rather than short fire intervals. Our results provide strong evidence that fire regimes rearrange fuel arrays in the years following fire, which suggests that future fire regime shifts may alter fuel states, with important implications for fuel and fire management.

Keywords: fire interval; fuel severity; fire regime; fuel; Sydney Basin Bioregion

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1. Introduction

In fire-prone regions, vegetation communities have coevolved with specific and often stable fire regimes for millennia [1,2]. Such fire regimes have shaped vegetation composition by selecting for a range of fire response traits that aid in fire tolerance and post-fire regeneration [3,4]. Plant species utilising different fire response traits are often tied to specific attributes of the long-term fire regime, and fire regime shifts have the potential to disadvantage those species [5]. For example, increased fire frequency will disadvantage species with long-interval requirements [3], and increases or decreases in fire severity (i.e., loss of above- or below-ground organic matter in response to fire) [1] can disadvantage species with physically dormant seeds that require specific fire intensities to stimulate germination [6].

Dramatic fire regime shifts have been observed across Earth's fire-prone regions over the last century due to anthropogenic pressures including climate change, inappropriate land management, increased ignition frequency and the suppression of Indigenous burning practices [7–9]. Rapid contemporary and future changes to fire regimes have the potential to alter the composition and structure of vegetation communities, which may compromise biodiversity and ecosystem resilience, and alter future fire regimes by breaking long-held interactions between fire and biota. For example, Buffel Grass (*Cenchrus ciliaris*) invasion in northern Australia decreases floristic diversity by increasing fuel loads and, subsequently, fire severity [10,11].

Mega-fires [12] that burn exceptionally large areas at high severities are becoming increasingly common across Earth's fire-prone landscapes [13–16]. Current climate models suggest that larger fire events will become an increasingly important component of future fire regimes in many areas [7,16]. Given this, a quantitative understanding of how resilient vegetation communities are to specific fire regime attributes (e.g., fire frequency, interval, severity, season) and environmental conditions (e.g., climate), which are projected to change [17], will better direct fire management actions.

The amount and structure of vegetation that fuels fire (i.e., fuel) impacts many aspects of fire behaviour, including rate-of-spread and fire line intensity [18]. In Australia, fuels are categorised into discrete groups characterising the vertical fuel profile (e.g., [19]). Surface fuels represent ground litter and near-surface fuels represent low-lying herbs which are connected from the ground to the top of the herbaceous layer. Surface and near-surface fuels are important drivers of fire ignition and spread because they sustain and propagate fires that burn from the ground up [20–22]. Elevated fuels represent midstorey plants (typically shrubs and basal resprouting trees) with foliage that is unconnected to the ground, but may extend to (but not include) the overstorey tree canopy, and bark fuels represent flammable bark held on tree trunks. Elevated and bark fuels are important drivers of fire intensity and severity because they allow flame transfer from the ground to the tree canopy [22–24]. Given that fuel treatments are commonly used to manage fire hazards globally [25], understanding how different aspects of the fire regime impact fuel recovery following fire, particularly large and extensive fires, is critical to inform appropriate fire management operations.

Australia's Black Summer fire season (September 2019–March 2020) resulted in the largest annual area burned in recorded history for the forested biomes of southern Australia (over 7 M ha). Twenty percent of temperate forest biomes burnt [26], with major negative impacts to environmental and human assets experienced across the burn area [13,26–29]. The fires followed a severe and extended drought with many areas experiencing the lowest rainfall totals in recorded history [30]. These dry conditions were a major influence on the extent and severity of the 2019–2020 fires [13,31]. The fires ended with the onset of three consecutive La Niña phases of the Southern Oscillation cycle. Well above average rainfall occurred throughout 2020–2022 [30], which is perceived to have promoted rapid post-fire vegetation growth, especially of obligate seeding shrubs in the midstorey.

Here, we determine how fire interval (a composite measure of inter-fire period and fire frequency) and severity were associated with various fuel attributes 2.5 years after the Black Summer fires. We focus on fire interval and severity because they are thought to affect fuel load and structure in the short-term [32–35], and are projected to change across large areas of eastern Australia over the next century [7]. We also focus on quantifying fuel recovery 2.5 years following fire because this is when rates of fuel accumulation are the greatest. For example, the Olsen curve predicts surface fuel loads to increase by 2.87 t/ha between 2.5 and 5 years post-fire, but only 0.5 t/ha between 12.5 and 15 years post-fire (here, for Sydney coastal dry sclerophyll forest) [36]. Therefore, understanding fuel recovery 2.5 years post-fire provides a good indicator of future fuel states (using predictive approaches such as the Olsen curve), which will be key for planning appropriate interventions in subsequent years.

Because vegetation provides fuel for fire, plant responses to future fire regime shifts will determine post-fire fuel arrays. Across the range of fire-prone Australian eucalypt forests, most overstorey trees (and many shrubs) survive fire and regenerate from buds held within branches and trunks (i.e., resprouting), with many species having full canopies within ~5 years following fire [37,38]. High-severity fire reduces the proportion of plants that resprout and the height of resprouting, delaying full canopy replacement. Conversely, a diverse subset of shrubs regenerates only via seeding (i.e., obligate seeders). Many of these species have extremely rapid growth and maturation rates and adults senesce relatively quickly following fire [5]. Many species also exhibit physical seed dormancy, with higher temperatures needed to stimulate germination [6]. A large range of other shrub species typically resprout following fire, often from basal lignotubers but also, in some cases, from epicormic buds on stems. Herbaceous species regenerate through resprouting and seeding, with many species reaching reproductive maturity before trees and shrubs, owing to rapid foliage production. Thus, aspects of individual fires and fire regimes will act to promote some species over others. Given this a priori knowledge, we test the following hypotheses:

1. Ground litter (surface fuels), tree canopy (canopy fuels) and tree bark (bark fuels) fuel load, cover and hazard will be highest after fires of low severities and long intervals due to lower rates of consumption during those fires;
2. Herbaceous (near-surface fuels) fuel cover and hazard will be highest after fires of high-severities and short-intervals due to selection for fast regenerating species;
3. Midstorey (elevated fuels) fuel cover and hazard will be highest after fires of high fire severities due to fire-stimulated germination of shrubs, and lowest at short inter-fire intervals due to exhaustion of shrub seed and bud banks.

For our purposes, fuel hazard refers to fuel arrays that may potentially facilitate a spreading fire given an ignition. Greater fuel hazard ratings are associated with greater potential fire behaviour such as flame height, rate of spread and spotting potential [2,3].

2. Materials and Methods

2.1. Study Area and Design

The study was conducted at 63 sites located in the Sydney Basin Bioregion of New South Wales (Australia; Figure 1), which is characterised by a temperate climate with warm summers, cool winters and no dry season. Mean annual air temperature and precipitation in the bioregion ranges from 10–17 °C and 522–2395 mm, respectively [39]. The region is primarily mountainous with a varied topography of sandstone mountain tops and plateaus up to 1200 m elevation above sea level, wide canyons and steep erosional gullies.

Sites were located across four classes of the dominant fire-prone dry sclerophyll forest (DSF) vegetation formation: Sydney coastal, Sydney hinterland, Sydney montane and Sydney sand flats DSF (sites per class); [40]. The vegetation classes occur in the same broad climatic regions and are dominated by similar lithology and floristic assemblages. However, at finer spatial scales, montane forests typically occur in moister higher elevation landscapes than coastal, hinterland and sand flat forests; hinterland and sand flat forests are typically drier than coastal forests. All field sites occurred on ridges or plateaus with infertile sandy soils and were last burned by wildfires between the 25 October 2019 and 4 January 2020, with the exception of one site burned by a prescribed fire on the 12 May 2020.

Within each vegetation class, sites were near-orthogonally replicated across two fire severity (high, low) and interval (short, long) categories, with three to four replicates within each severity and interval combination. Fire severity was defined by the degree of overstorey canopy consumption during the Black Summer fires using the New South Wales Fire Extent and Severity Mapping (FESM) maps [41,42]. In our study, low fire severity represented sites burned by understorey fire that did not extend to the overstorey tree canopy (low, moderate FESM classes), and high fire severity represented sites burned by overstorey fire that caused tree canopy scorch or consumption (high, extreme FESM classes). The remotely sensed fire severity classification was validated using visual estimates of percent canopy consumption by fire.

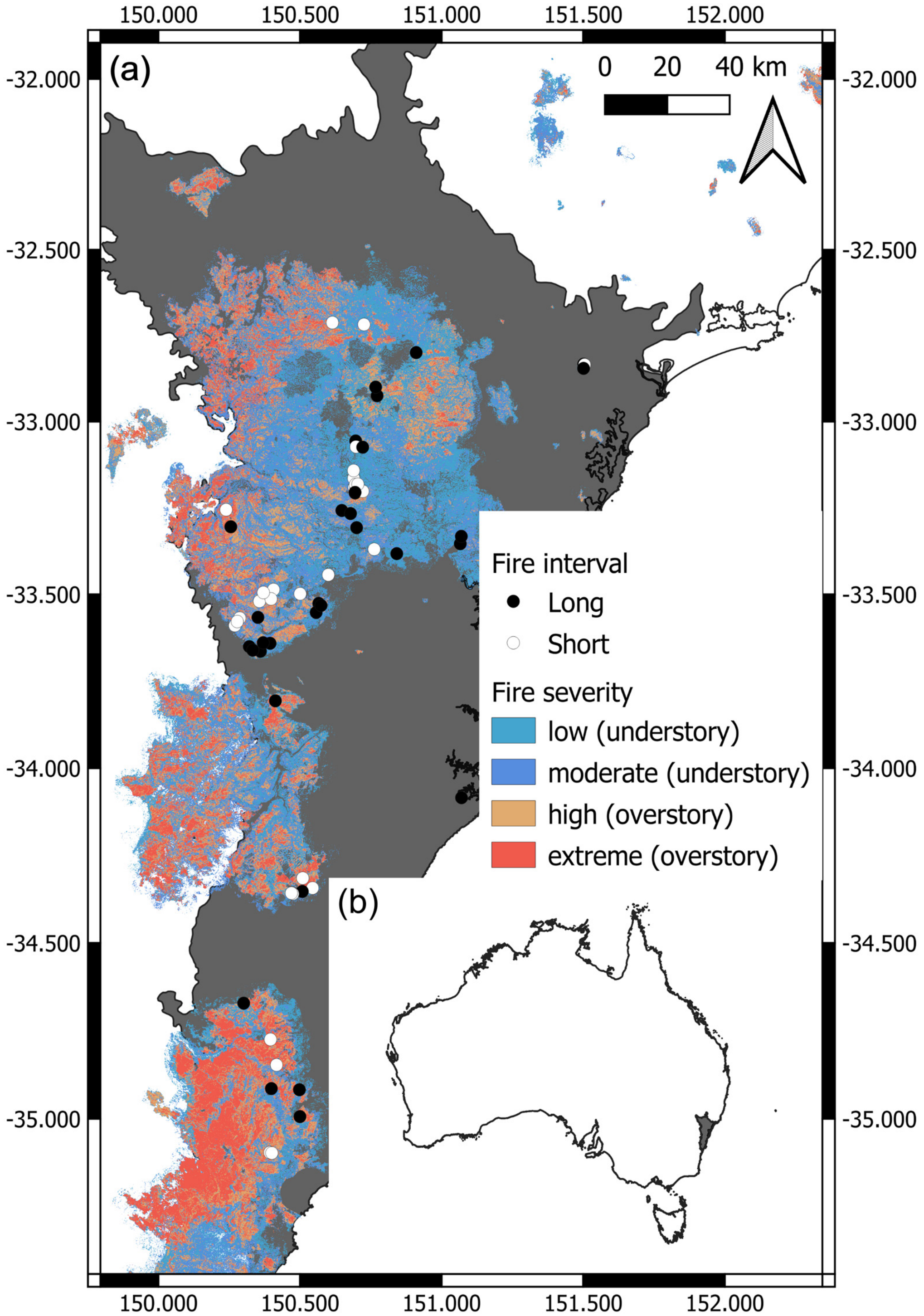

Figure 1. (**a**) Map of the study area in the Sydney Basin Bioregion showing the location of 63 sites (points) where fuel recovery was assessed following the 2019–2020 Black Summer fires. Field sites were stratified by fire interval (long, short) and fire severity (understorey: low, moderate; overstorey fire: high, extreme), indicated in the underlying map. (**b**) Map shows the location of the Sydney Basin Bioregion (grey polygon) in south-east Australia.

Fire interval was defined as a composite of the period between consecutive fire events and the number of fires over the past ~20 years. In our study, long fire intervals represented sites with a >10 year period between the last two fire events (i.e., the Black Summer fire and the previous fire; mean 18.75 ± SD 6.81 years across sites), and short fire intervals represented sites with a <10 year period between each of the last three fire events (first fire interval mean 6.45 ± SD 1.14 years across site, second fire interval mean 6.74 ± SD 2.23 years across sites). A fire interval of <10 years was chosen because this represents a threshold of potential concern for species loss in these vegetation communities [43]. Fire intervals were extracted from a fire history layer provided by the New South Wales Rural Fire Service [44].

At each field site, various measurements of fuel load, structure and hazard were performed within five discrete fuel strata representing the vertical profile of the fuel column: surface (ground lying live and dead vegetation <6 mm diameter), near-surface (live and dead vegetation with continuous fuel connection from the ground to 50 cm height; grasses, herbs and forbs), elevated (live and dead vegetation with a distinct gap between the lower branches and ground; typically shrubs and basal resprouting trees), canopy (live and dead vegetation within the overstorey tree canopy) and bark (bark held on tree stems that provides opportunities for fire to reach the tree canopy; [19]).

All fuel assessments were performed along two parallel 50 m transects spaced 40 m apart (henceforth the 50 m × 40 m plot). Each transect had a 10 m × 10 m quadrat at each end inside the plot. Two 2.5 m × 2.5 m sub-quadrats were located at the corners of each 10 m × 10 m quadrat closest to the 0 m mark of the 50 m transect. Therefore, there were two 10 m × 10 m quadrats and four 2.5 m × 2.5 m sub-quadrats on each transect (see Figure A1 for schematic of plot design). Transect was the replicate unit used in all statistical analyses (see below).

All field surveys were conducted between the 28 May and 14 December 2022, with a mean time-since-fire of 2.6 ± SD 0.14 years across sites (for convenience, henceforth (and above) referred to as 2.5 years post-fire).

2.2. Surface Fuel Load

Surface fuel load was assessed within each of the four 2.5 m × 2.5 m sub-quadrats at each site transect by collecting all dead ground-lying vegetation (diameter < 6 mm) falling within a 50 cm × 10 cm area. All samples were stored in paper bags before being dried at 60 °C for one week in a laboratory oven. After drying, the dry weight of each sample was measured in grams and summed across the four samples collected at each transect. A final weight per unit area was then calculated in tonnes per hectare. The surface fuel loads measured in our study were compared to those predicted using the Olson curve [36], which calculates fuel load as a function of time-since-fire and fuel input and decay. The Olson curve is operationally used by government agencies for fuel load prediction across Australian forests.

2.3. Fuel Cover, Connectivity and Height

A line intercept method was used to assess the cover, vertical connectivity and height of surface, near-surface, elevated and canopy fuels at each site transect. At 1 m intervals along each of the 50 m transects, the presence and maximum height (cm) of vegetation intercepts was recorded within five height classes using a 2 m tall pole: 0 cm–19 cm, 20 cm–49 cm, 50 cm–99 cm, 100 cm–149 cm and 150 cm–200 cm above the ground. The presence of live and dead overstorey vegetation > 4 m height was also recorded at each point within the focal view of a densitometer (Geographic Resource Solutions) and the presence of ground surface fuel was recorded at the base of the 2 m pole. When present, litter depth was measured using a small ruler as the distance between the top of the litter bed and the underlying ground.

The line intercept data were used to calculate the following variables at each transect: surface fuel (leaf litter, twigs) and live and dead tree canopy fuel cover (percentage of points where intercepts were recorded), near-surface fuel cover (percentage of points where at least one grass or herb intercept was observed between 0 cm–49 cm height), near-surface fuel vertical connectivity (percentage of points where at least one live or dead grass or herb intercept was observed within both the 0–19 cm and 20 cm–50 cm height classes), elevated fuel cover (percentage of points where at least one live or dead intercept was observed between 50 cm–200 cm height), elevated fuel vertical connectivity (percentage of points where at least one intercept was observed within all of the 50 cm–99 cm, 100 cm–149 cm and 150–200 cm height classes), near-surface and elevated vertical connectivity (percentage of points where at least one intercept was observed within all near-surface and elevated height classes), mean maximum elevated fuel height (cm) and mean litter depth (mm).

2.4. Tree Basal Area

Tree basal area was assessed by measuring the diameter over bark at 130 cm height above the ground (henceforth DBH) of all tree trunks with a DBH $\geq$ 15 cm and a height of $\geq$2 m within a 50 m $\times$ 20 m sub-plot, typically located on the downslope side of the 50 m $\times$ 40 m site plot. Tree basal area per site (not transect) was calculated (m^2) by summing each tree's basal area (Equation (1)).

$$\mathrm{TBA}(\mathrm{m}^2) = \sum \pi \mathrm{r}^2;\ \mathrm{r} = \mathrm{DBH}/2 \tag{1}$$

2.5. Fuel Hazard

Surface, near-surface, elevated and bark fuel hazard were assessed within each of the 10 m $\times$ 10 m quadrats using a commonly employed visual ranking guide [19]. The fuel hazard guide uses qualitative estimates of fuel cover, fuel connectivity, fuel dead-to-live ratio, litter depth and percentage combustible bark to assess fuel hazard within each fuel strata as low, moderate, high, very high or extreme.

All fuel hazard scores were converted to numbers (low = 1, moderate = 2, high = 3, very high = 4, extreme = 5), then averaged between the two 10 m $\times$ 10 m quadrats at each transect (rounded up to the closest whole number). The final fuel hazard scores were treated as ordinal factors in all analyses.

2.6. Data Analyses

Separate generalised linear mixed-effects models were used to quantify associations between our fuel variables and fire interval, fire severity and vegetation class. We used a Gaussian distribution for surface fuel load, surface fuel cover, litter depth, near-surface cover, near-surface vertical connectivity, elevated cover, elevated mean maximum height and live canopy cover, and a Poisson distribution for elevated vertical connectivity, dead canopy cover and near-surface and elevated vertical connectivity. To be conservative with degrees of freedom in our models, only additive effects were considered; model interactions between the focus fire variables were also shown to be non-significant in preliminary analyses. All models included tree basal area as a fixed effect to account for differences in tree density/cover across sites. All models included a site-level random effect (n = 63) to account for the nested study design. Chi-squared (χ^2) and associated p-values from ANOVA tables were used to assess statistical significance (alpha = 0.05). Model fit was assessed using marginal pseudo-R^2 values, which describe the proportion of variance explained by fixed factors in a model.

Due to the ordinal response of the fuel hazard data, separate ordinal mixed-effects regression models (cumulative link mixed models; CLMM) were used to quantify associations between surface, near-surface, elevated and bark fuel hazard and fire interval, fire severity, vegetation class and tree basal area. Because very high and extreme fuel hazard scores were rarely observed (as expected soon after fire), we pooled these fuel hazard categories for surface, near-surface and elevated fuel hazard. Similarly, we pooled high and very high fuel hazard scores for bark fuels (extreme fuel hazard scores were absent). Pseudo-R^2 values could not be computed for the CLMMs.

Statistical models were fit in the R program (version 4.2.2) using the "car" [45], "lme4" [46], "MuMIn" [47] and "ordinal" [48] packages.

3. Results

Significant associations were observed between most of the fuel variables and either fire interval or severity, and responses could be broadly grouped within fuel strata (Table 1).

Table 1. Results from statistical models testing associations between various response variables and fire interval, fire severity, vegetation class and tree basal area (TBA). Numbers show Chi-squared (χ^2) and associated *p*-values (* p = 0.05–0.01, ** p = 0.01–0.001, *** p = <0.001). Generalised linear mixed-effects models were fit for all response variables except surface, near-surface, elevated and bark fuel hazard where cumulative link mixed-models were used. For the mixed-effects models, model fit was assessed using marginal pseudo-R^2 values. - shows cells where pseudo-R^2 values were not present.

Fuel Strata	Response Variable	Predictor Variables				Fit
		Severity	Interval	Vegetation	TBA	
Surface	Fuel load (tha^{-1})	9.99 **	<0.01	6.05	6.33 *	0.26
Surface	Fuel cover (%)	18.08 ***	0.01	9.41 *	0.13	0.27
Surface	Mean litter depth (mm)	0.42	1.02	2.65	<0.01	0.05
Surface	Fuel hazard (l, m, h, vh/e)	2.07	0.11	3.04	1.06	-
Near-surface	Fuel cover (%)	0.05	2.31	3.31	0.17	0.08
Near-surface	Fuel vertical connectivity (%)	0.45	2.19	8.00 *	0.56	0.14
Near-surface	Fuel hazard (l, m, h, vh/e)	4.27 *	0.52	9.99 *	0.41	-
Elevated	Fuel cover (%)	9.96 **	11.47 ***	13.24 **	0.53	0.28
Elevated	Fuel vertical connectivity (%)	1.92	15.75 ***	18.09 ***	0.94	0.35
Elevated	Mean maximum fuel height (cm)	1.14	12.26 ***	4.38	0.12	0.19
Elevated	Fuel hazard (l, m, h, vh/e)	9.22 **	6.58 *	3.68	0.152	-
Near surface–Elevated	Fuel vertical connectivity (%)	3.94 *	7.22 **	12.73 **	0.34	0.34
Canopy	Live fuel cover (%)	38.93 ***	0.86	7.26	0.04	0.42
Canopy	Dead fuel cover (%)	5.78 *	0.61	4.84	1.44	0.14
Bark	Fuel hazard (l, m, h/vh)	6.94 **	3.66	7.29	1.20	-

Surface fuel variables were associated with fire severity but not interval (Table 1). Significant associations were observed between surface fuel load and cover and fire severity, with lower values observed in areas burned at high rather than low severities (Table 1, Figure 2a,b). Non-significant associations were observed between all surface fuel variables and fire interval, and mean litter depth and surface fuel hazard and fire severity (Table 1).

Most near-surface fuel variables were not associated with fire interval or severity, with non-significant effects observed in our statistical models (Table 1). However, a significant association was observed between near-surface fuel hazard and fire severity, with the frequency of higher fuel hazard scores (high, very high, extreme) more commonly observed in areas burned at low rather than high fire severities (Table 1, Figure 3a).

Elevated fuels were more strongly associated with fire interval than severity; however, significant associations were also observed with fire severity (Table 1). Significant associations were observed between all elevated fuel variables and fire interval, with elevated fuel cover, fuel vertical connectivity, mean maximum height and the frequency of higher fuel hazard scores (high, very high, extreme) higher in areas burned at long rather than short fire intervals (Figures 2c–e and 3b). Significant associations were observed between elevated fuel cover and elevated fuel hazard and fire severity, with elevated fuel cover and the frequency of higher fuel hazard scores (high, very high, extreme) higher in areas experiencing high- rather than low-severity fire (Table 1, Figures 2c and 3c). Non-significant associations were observed between elevated fuel vertical connectivity and mean maximum elevated fuel height and fire severity (Table 1).

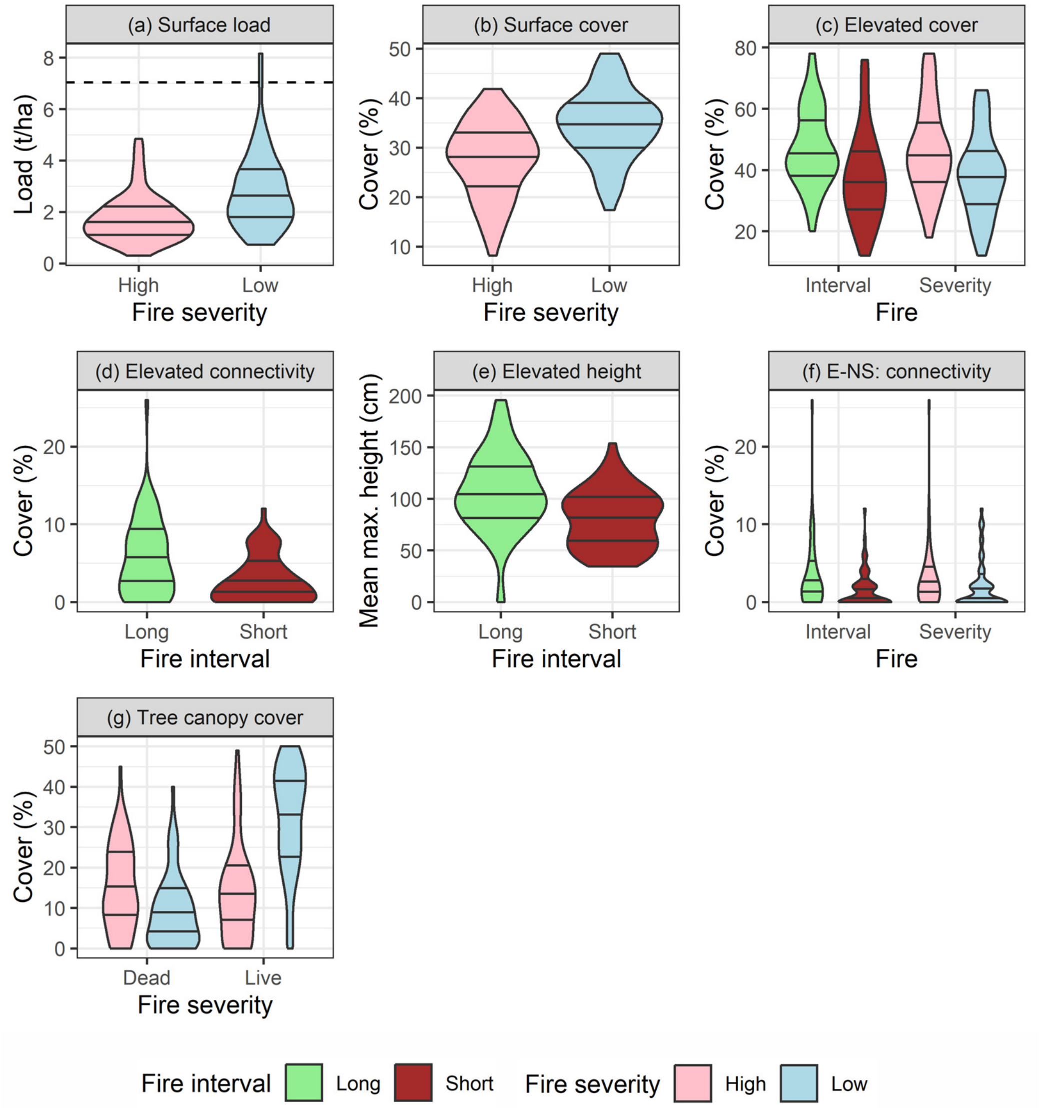

Figure 2. Associations of fire interval and/or severity to: (**a**) surface fuel load, (**b**) surface fuel cover, (**c**) elevated fuel cover, (**d**) elevated fuel vertical connectivity, (**e**) elevated mean maximum fuel height, (**f**) near-surface and elevated fuel vertical connectivity, and (**g**) dead and live tree canopy cover. Only significant associations from Table 1 are shown. Violin plots show the range (height) and density (width) of transect-level data and the 25th, 50th and 75th percentiles are shown as horizontal lines. For (**a**), the dashed line shows fuel load predictions made using the Olson curve.

The vertical connectivity of both near-surface and elevated fuels was significantly higher in areas burned at long rather than short fire intervals and in areas experiencing high rather than low-severity fire (Table 1, Figure 2f).

Tree canopy fuels were more strongly associated with fire severity than interval (Table 1). Significant associations were observed between live and dead tree canopy fuel cover, with live canopy fuel cover lower in areas burned by high- than low-severity fire, but dead fuel cover higher in areas burned by high- than low-severity fire (Figure 2g). Non-significant associations were observed between live and dead tree canopy fuel cover and fire interval (Table 1).

A significant association was observed between bark fuel hazard and fire severity, with the frequency of higher fuel hazard scores (high, very high) higher in areas experiencing low- rather than high-severity fire (Table 1, Figure 3d).

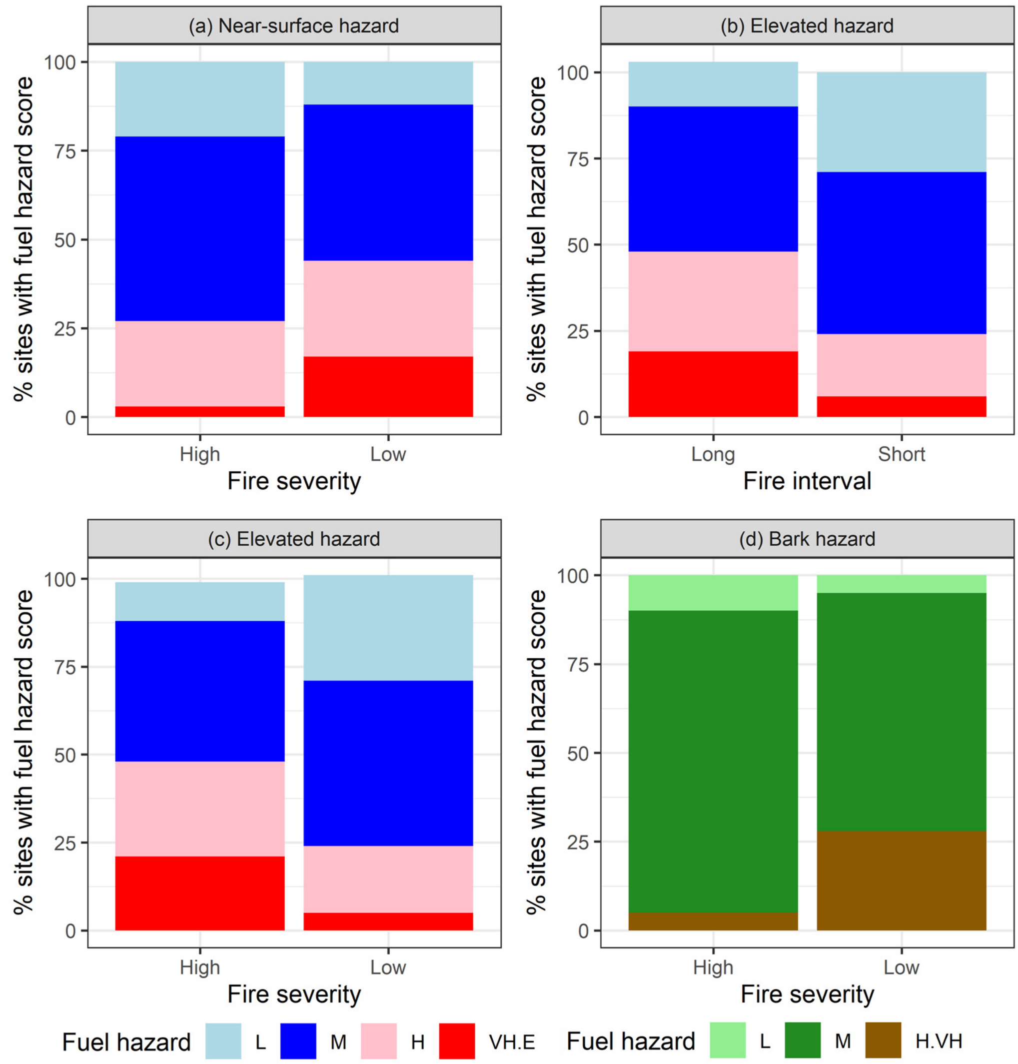

Figure 3. Associations between fire severity and (**a**) near-surface, (**c**) elevated and (**d**) bark fuel hazard and fire interval and (**b**) elevated fuel hazard. For (**a**–**c**), L: low, M: medium, H: high, VH.E: very high or extreme. For (**d**), L: low, M: medium, H.VH: high or very high. Only significant associations from Table 1 are shown. Bar plots show the percentage of field sites falling within fuel hazard score groups.

4. Discussion

Our results indicate that fire regimes have widespread impacts on fuel arrays in the years following wildfire, in ways that were mostly consistent with our a priori predictions. In agreement with our predictions, ground (surface) fuel cover and load, overstorey tree canopy fuel cover and herbaceous (near-surface) and bark fuel hazard scores were lower in forests burned by high rather than low-severity fire. This is presumably due to higher levels of fuel consumption (and lower amounts of residual fuels; i.e., those left unburned; [49]) in areas burned by high- rather than low-severity fire [34]. Midstorey (elevated) fuel cover and fuel hazard scores were higher in areas burned by high- rather than low-severity fire, presumably because high-severity fire stimulated the mass recruitment of shrubs requiring high temperatures to facilitate seed germination [6]. Elevated fuel cover, vertical connectivity, max. height and fuel hazard scores were also lower in forest burned by short rather than long fire intervals, presumably because multiple short-interval fires killed obligate seeding shrubs before maturation; and hence, exhausted seed banks and regeneration vigour [50]. In contrast to our predictions, only elevated fuels were associated with fire interval, and most near-surface fuel measures were not associated with fire interval or severity.

Our results were consistent with other studies of Australian eucalypt forest showing higher surface and elevated fuel consumption in areas burned by high- rather than low-severity fire [34], higher amounts of surface fuels remaining unburned in areas burned by low- rather than high-severity fire [34], and higher elevated fuel loads in areas burned by high- rather than low-severity fire [32]. However, they contrast with a study showing that surface and elevated fuel loads were not associated with fire severity 1 year following the Black Summer fires [51]. This probably occurred because, in our study, surface and elevated fuels had more time to respond after the fires. Our results improve our knowledge about post-fire responses to fire by further describing fire severity effects on multiple fuel strata and highlighting previously unrecorded associations between fire interval and elevated fuel cover.

4.1. Fuel Recovery and Fire Hazard

In Australia, post-fire fuel accumulation is generally predicted using a simple negative exponential model (i.e., the Olson Curve; [36]). The model predicts that standing fuel loads are a function of time-since-fire within different vegetation categories, and that the rate of fuel accumulation is higher in the years immediately following fire (generally <10 years in dry sclerophyll forests) than at older post-fire ages where fuel loads reach a steady-state plateau (generally ~20 years in dry sclerophyll forests; [52]) or slightly decrease [24].

Our field assessment was conducted 2.5 years after the Black Summer fires, and, thus, characterises fuel states at the beginning of a period of exceptionally rapid fuel accumulation [36], but also a period when overall fuel hazard is assumed to be relatively low, as predicted by operationally used fuel prediction models [36]. Reduced fuel load and fuel vertical connectivity in the years following fire can constrain subsequent fire activity in dry sclerophyll forests because there is less fuel to burn [53,54]. These periods of reduced fuel hazard are crucial for landscape scale fire planning and mitigation because they represent times where subsequent wildfires are less likely to occur. However, our understanding of factors impacting the duration of these periods is poor.

Our results clearly show that fire interval and severity strongly impact fuel arrays at younger fuel ages. In particular, our results suggest that dense regrowth of midstorey (elevated) fuels following high-severity, short-interval fire may result in relatively high fuel hazard at younger fuel ages. The higher residual fuel loads (i.e., surface, near-surface and elevated fuel left unburned by the 2019–2020 fires) observed at sites burned by low-severity fire may also result in a relatively high fuel hazard in these areas.

How fuel loads and hazard will continue to change into the future will depend on many factors, including topographic position, climate, other aspects of the historical fire regime and interactions between fuel strata (e.g., [55]). Given exponential increases in fuel accumulation through time [36], and when considered with other studies, our results suggest that surface fuel loads and possibly rates of surface fuel accumulation will be relatively low over the coming decades in areas burned by high- compared to areas burnt by low-severity fire. Further, elevated fuel loads and possibly rates of elevated fuel accumulation should be relatively low in areas burned by low- compared to areas burnt by high-severity fire, and areas burned by long-- compared to short-interval fire. Operationally used fuel models such as the Olson curve currently provide coarse-scale fuel load predictions irrespective of differences in historical fire regime. Our study suggests that incorporating additional factors such as fire interval and severity as covariates in models provides great promise to increase the accuracy of fuel load prediction across large spatial and temporal scales.

The impact that post-fire fuel arrays will have on overall fire hazard and operational fire hazard prediction, both in the short- and long-term, will depend on interactions between fuel strata themselves and meteorological conditions promoting fire spread. Fire behaviour models have traditionally prioritised surface and near-surface fuel loads when predicting overall fuel hazard [36,56]. However, elevated fuel load/structure and overall fuel vertical connectivity are increasingly being recognised as key drivers of fire behaviour [24,57].

In line with this work, recent models have placed a greater emphasis on elevated fuels, and fuel vertical connectivity more generally [58,59]. Recent (and some older) research has also highlighted the important role that fire weather has in moderating fuel impacts on fire behaviour. For example, fuel load may limit fire spread during more benign fire weather conditions (relatively cool, humid and still) when rates of fire spread are driven by surface fuel load and vertical flame progression; however, not during extreme fire weather (relatively hot, dry and windy) when fires can horizontally propagate through elevated fuel, irrespective of surface fuel load [57,60,61]. Such fine-scale effects are also being considered in contemporary fire behaviour models (e.g., [57]).

Based on our findings, we predict that overall fire spread potential at 2.5 years post-fire and under moderate fire weather conditions should be relatively low, irrespective of the severity of the last fire. This is because fuel loads are low, sparse and insufficient to facilitate flame transfer under moderate fire weather. However, during more extreme fire weather conditions, which are projected to increase in frequency in the near future [7], elevated fuels may vertically and horizontally propagate fire [24,57]. Given this, fire potential may still be high at times in the years immediately following fire, particularly in areas burned by high-severity or long-interval fire where elevated fuel loads and vertical connectivity are high. It is important to note that, although elevated fuel hazard may be relatively high in areas experiencing high-severity or long-interval fire, fuel load and vertical connectivity will still be lower than those present at older fuel ages [36]. Therefore, it is unlikely that large, uncontrolled wildfires (like the Black Summer fires) will occur until fuel arrays increase and bypass fuel limitations on fire spread.

The longer-term impacts that fire interval and severity have on the trajectory of overall fuel and fire hazard through time are contingent upon plant species (and, hence, fuel) resilience to changing fire regimes and climates. Such pathways of possible change are discussed below.

4.2. Future Fire Regimes and Fuel States

Current models suggest that eastern Australia will experience increased climate variability in the near future, with subsequent increases in drought and flood frequency and severity [7,62]. Such climatic variability is predicted to increase the frequency of large, high-severity fire events and seasons (like the Black Summer fires) because high-rainfall events are hypothesised to promote high fuel loads across large areas, and subsequent drought conditions are hypothesised to allow this fuel to dry out and become available to burn [60]. Further, the frequency of extreme fire weather conditions that facilitate fire spread are also expected to increase in the near future [7]. In response to the increasing fire danger, fire management agencies will continue to utilise prescribed fire to mitigate risk to people, infrastructure and environmental values. The rightful restoration of Indigenous cultural burning after two centuries of active persecution and suppression will add complementary fire to the landscape [63]. Understanding how vegetation communities and their fuel load and structure will respond to future climates, and potential fire regimes, will be key for the long-term planning and management of future fire risk.

Our results suggest that currently projected climate and fire regimes have the potential to promote vegetation states with markedly different fuel arrays to those currently present in eastern Australia's dominant dry forests. Figure 4 describes a plausible state-and-transition model describing how fire regimes and regime shifts may impact fuel states. The model proposes that fire regime shifts that promote frequent (future) rather than relatively infrequent (current) high or mixed severity fire may be a key driver of fuel state shifts. Such a shift would involve a transition from current-day shrubby forms of dry sclerophyll forests [40] where fuel is often connected between the understorey herbaceous, midstorey shrub and sometimes overstorey tree fuel layers, to more open forms of dry sclerophyll forests [40] where midstorey shrubs are relatively sparse or patchy and understorey herbaceous and overstorey tree fuels are disconnected. This transition would primarily be driven through the selection for herbaceous species with fast growth and reproduction rates that can persist through short-interval and often high-severity fire, rather than obligate seeding and resprouting shrubs that require longer maturation periods or times to replenish storage reserves [3,5,33].

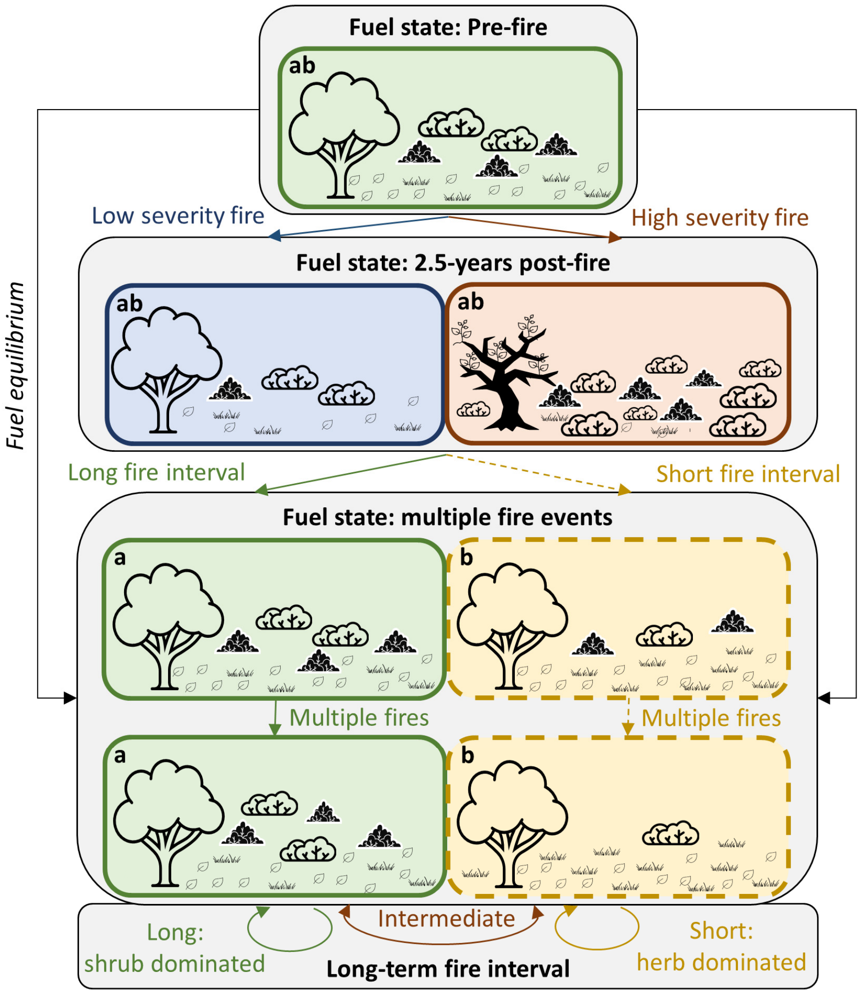

Figure 4. Hypothesised state-and-transition model describing how fire regime shifts may impact dry forest fuel states in south-eastern Australia. Low- or high-severity fire differently impacts fuel states in the years following fire (pathway ab; solid lines; low = blue fill, high = red fill), with high-severity fire promoting denser midstorey fuel load/connectivity due to fire-stimulated shrub seed/bud regeneration, and sparser litter and herb fuel load/connectivity due to fuel consumption. Fuel arrays return to pre-fire states given long fire return intervals owing to shrub maturation and tree canopy regrowth (pathway a; solid lines; green fill), irrespective of fire severity. However, fuel arrays transition to a more open state given multiple high- or low-severity short-interval fires (pathway b; dashed lines; yellow fill). This is because short-interval fire kills shrubs before maturation, depleting seed/bud banks and regeneration vigour. Herbaceous fuel load/connectivity may then increase due to competitive release and herb resilience to short-interval fire. The recurrence of long- or short-interval fire determines fuel states, with intermediate states present when recurrent short-interval fires are followed by long-interval fire.

In the model, we propose that state-changes are contingent on shrub and herb recruitment following repeated short-interval fire. It is likely that future fire regimes will oscillate between periods of recurrent short- or long-interval mixed-severity fire based on climatic limitations on fuel growth and subsequent fire feedbacks, with concurrent changes in fuel structure and array. However, the targeted application of short-interval fire around high value assets through prescribed fire and/cultural burning, on top of wildfires, will undoubtedly occur in many locations. The state change shifts proposed by the model would be particularly relevant to these areas where recurrent short-interval fire dominates the landscape.

It is important to note that the hypothetical state-and-transition model requires further testing using observational and modelling approaches. For example, field-based assessments comparing fuel states across a broad range of short-interval fire frequencies through time, simulations that predict fuel state changes given modelled fire regime shifts, and germination experiments that investigate recruitment success and competitive interactions between shrubs and herbs are required to thoroughly evaluate such a model. The model is based on empirical data collected 2.5 years post-fire only and assumes continued post-fire regeneration thereafter. Therefore, it provides a starting point to facilitate such assessments.

5. Conclusions

Australia's Black Summer fires are indicative of current and future fire regimes expected in many fire-prone forests globally. Understanding how fuel loads recover following such fires will be important for fire management actions aiming to mitigate impacts on human and environmental assets. Our results suggest that fire interval and severity are important drivers of post-fire fuel load, cover, vertical connectivity and hazard 2.5 years after an extensive and often high-severity mega-fire. Midstorey elevated fuels were promoted under conditions of high-severity and long-interval fire, and ground litter or surface fuels were promoted under conditions of low-severity fire. These results were incorporated in our state-and-transition model, and imply that future fire regimes dominated by persistent short-interval high-/low-severity fires may lead to vegetation, and, subsequently, fuel state changes, perhaps favouring open-forest types.

As with other correlative studies, our results require further validation using experimental and longitudinal studies. However, they add to a growing body of literature aiming to address a key issue in future fire and conservation management: How will future climates and fire regimes impact stable vegetation states, and how should we protect environmental and human assets in a changing world?

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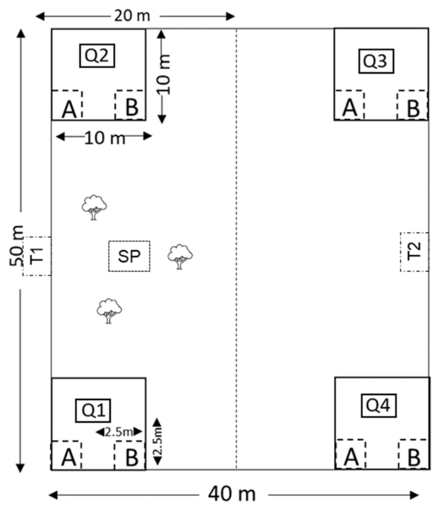
Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A



Abbrev.	Name	Size	Sampled
SP	Subplot	50 m x 20 m	Tree basal area
T.1-2	Transect	50 m	Fuel cover, connection, height
Q.1-4	Quadrat	10 m x 10 m	Fuel hazard
SQ.A-B	Sub-quadrat	2.5 m x 2.5 m	Litter load

Figure A1. A schematic showing the field plot design. Fieldwork was conducted within a 50 m × 40 m plot, with subplots (SP), transects (T), quadrats (Q) and sub-quadrats (SQ) nested within plots. Different fuel attributes were sampled (Sampled) within each plot, subplot, transect, quadrat, and sub-quadrat.

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