An examination of fire history and fire management in the context of fauna conservation in south-eastern Australia

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An examination of fire history and fire management in the context of fauna conservation in south-eastern Australia

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Statement of Authorship and Sources

This thesis contains no material that has been extracted in whole or in part from a thesis that I have submitted towards the award of any other degree or diploma in any other tertiary institution.

No other person's work has been used without due acknowledgement in the main text of the thesis.

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Jane Williamson

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Abstract

Fire can influence biodiversity by changing the spatial patterns of vegetation and the suitability of habitat for fauna species. Understanding the spatial patterns of fire in the landscape is critical to the conservation of biodiversity, and this is reliant on sound knowledge of fire history.

In this thesis I examined fire history and fire management in the context of fauna conservation in New South Wales (NSW), south-eastern Australia. Initially, I used digital fire records for NSW for years 1902 to 2018 to identify sources of error in the database, then examined how data quality may affect interpretation of fire history for biodiversity conservation. I then examined variation among, and predictors of, distributions of time since the most recent fire (TSMRF) for extant native vegetation in NSW. I tested whether distributions of time since fire for different vegetation types follow predicted trends at varying scales and identified the degree to which these distributions are influenced by landscape management actions. Finally, I used a field-based study to investigate the impacts of fire history, vegetation type, and environmental factors on habitat attributes, and the extent to which they vary among vegetation types.

Thirty-two years and 76% of extant native vegetation in NSW (38% in areas managed for biodiversity conservation) had no fire records, and significantly more in the drier, less populated western parts of the state. However, my results indicate this is an incomplete representation of fire history. Repeated records accounted for >50% of the records in the database, however only 8% were identified by an automated clean using software tools. Without a manual-clean the number of fires and area burnt per year would be exaggerated by >300% in some years. The number of repeated records and records with missing data reduced dramatically from the early 2000s.

After cleaning, change point analyses indicate two periods of change in the patterns of recorded area burnt, the mid-1930s and late-1960s, although it remains unclear whether this is a change in fire regime or improved record keeping. Ninety-one percent of records were missing attributes important for biodiversity conservation (month of fire occurrence and intensity), severely limiting the usefulness of the database for biodiversity management, planning, and research.

In 2018, TSMRF varied from 0 to 92 years. TSMRF was skewed to shorter intervals in 2018, 2008 and 1998. In more coastal eastern areas, distributions were skewed to shorter times since fire but were similar among wet and dry vegetation types. In arid and semi-arid areas, distributions were greatly variable but skewed to longer TSF than more coastal areas and were often heavily influenced by one or two large fire events.

At a local scale, distributions of TSMRF varied within vegetation types that spanned large geographic areas. At a finer scale still, distributions were similar in locations in close proximity, regardless of vegetation type. Within areas managed for biodiversity conservation, distributions of TSMRF were skewed to shorter times since fire than in general for the vegetation type. Previous fire history, mean annual temperature and rainfall, and land-use were stronger predictors of the distribution of time since fire than proximity to roads and population density.

Although similar in structure and physiognomy, it was the floristic and fine-scale structural differences that were the greatest drivers of variation in habitat in the three vegetation types I examined. Characteristics of the most recent fire and the interval to the next fire did not have as strong an effect on habitat as vegetation type. The fire type (wild versus prescribed) was one of the best predictors for variation in the landscape for some habitat types. There was a weaker, but significant effect on fauna habitat of time unburnt prior to a fire and whether the fire is wild or prescribed. However, these effects of fire varied among vegetation types.

My findings demonstrate that key habitat types important for the persistence of fauna did not have a uniform response among vegetation types at a local scale. Fire management practices designed for managing plant species survival are based on predictable plant responses to fire at a formation-scale, however these results demonstrate that the response of key fauna habitat attributes is not predictable at this scale and fire management may need to be directed at a finer-scale than that at which they are currently managed.

Chapter 1 General Introduction

Fire is an intrinsic ecological process of many landscapes across the world (Agee 1996; Singh *et al.* 2002; Moritz *et al.* 2014), shaping the distribution of vegetation in many biomes (Bond *et al.* 2004). The ecological sustainability of over 50% of the world's terrestrial habitats is reliant on fire (Shlisky *et al.* 2009) and fire can have significant impacts on the composition, diversity, structure, distribution, and function of ecosystems (Ellis 1985; Fensham *et al.* 2003; Staver *et al.* 2011). Inappropriate fire regimes are a growing threat to and are listed as a key threatening factor in the decline of many species in Australia (Evans *et al.* 2011; Woinarski *et al*. 2015). Inappropriate fire regimes (e.g., the exclusion of fire or too frequent fire) and can have negative consequences for biodiversity including loss of species and habitat (Woinarski 1999; Bond and van Wilgen 1996; Wilson 1996). Fire can influence biodiversity by altering the spatial patterns of vegetation and composition of plant species (Morrison *et al.* 1995; Bond and van Wilgen 1996), and the suitability of habitat for fauna species (Catling 1991; Fox 1982). Time since fire influences habitat suitability in many ecosystems (Fox 1982; Kelly *et al.* 2011; Watson *et al.* 2011) but can be affected by fire frequency, inter-fire interval, intensity, and season (Gill and Allan 2008). Interactions among variations in climatic and environmental conditions, vegetation type, and the fire regime cause fires to vary spatially and temporally in the landscape (Murphy *et al.* 2013) which can influence the availability of habitat. The complexity of the spatial patterns of a fire regime increases with the overlapping of multiple fires through time in the landscape. As such, an understanding of the patterns of fire at various scales in the landscape is critical to the conservation of biodiversity, and this is reliant on sound knowledge of fire history.

1.1 Fire in the landscape

Fire is a key, but not uniform influence on native vegetation and ecosystem function around the world (Bond and van Wilgen 1996; Bowman *et al.* 2009). The main governing mechanisms of the temporal and spatial arrangement of fires in the landscape are environmental and climate conditions, distribution of fuels, and ignition agents (Cary *et al*. 2006; Whitlock *et al*. 2013) and the relative influence of these drivers varies at different scales (Simard 1991; Falk *et al.* 2007).

1.1.1 Climatic and environmental influences on fire

Over small spatial scales and over the short-term, fire ignition, extent and intensity are related to fine scale weather and moisture conditions (wind speed, air temperature, humidity) and fuel type (Rothermel 1972). At a landscape scale, seasonal and long-term climate, vegetation type and topography influence moisture patterns which determine the availability of fuels (Rollins *et al*. 2002; Schoennagel *et al.* 2004; Mermoz *et al.* 2005; Crimmins 2006; Murphy *et al.* 2013). At a regional or global scale fire occurrence follows a productivity gradient (Pausas and Bradstock 2007; Krawchuk and Moritz 2011; Lehmann *et al*. 2011; Murphy *et al.* 2013) and interactions between climate conditions and fuels lead to varying fire patterns within different biomes (French *et al*. 2002; Flannigan *et al.* 2005; Harris *et al.* 2008). Variation in these key drivers leads to heterogeneity in fire patterns within and among vegetation types (Meyn *et al*. 2007; Krawchuk and Moritz 2011).

1.1.2 Anthropogenic influence on fire

Humans have impacted fire regimes over evolutionary time by influencing the number and arrangement of fires by increasing ignition rates or fire suppression, by changing land use and cover, and hence fuel arrangement, continuity, and availability (Spies *et al.*2004; Marlon *et al*. 2008; Bowman *et al*. 2011), and indirectly through changes to global climate (Flannigan *et al.* 2009; Jolly *et al.* 2015).

Anthropogenic ignitions are the main cause of wildfires in many regions (e.g., southern Europe: Henderson *et al.* 2005; Russia: Mollicone *et al.* 2006; Alaska: Todd and Jewkes 2006; southern China: He *et al.* 2013) and have been found to increase with proximity to areas of high population (Niklasson and Granstrom 2000; de la Cueva *et al.* 2006; Sypahrd *et al.* 2007; Yang *et al.* 2007; Chas-Amil *et al.* 2013) and road densities (Huang *et al.* 2000; Pew and Carson 2001; Romero-Calcerrada *et al.* 2008; Liu *et al.* 2012; Kolanek *et al.* 2021), particularly in the tropics (Cochrane *et al.* 1999).

However, the impact of humans on the fire regime varies across the landscape, and the relationship between human factors and the occurrence of fire is not linear. Changes in land-use have led to increased fire activity in some regions (Cochrane *et al.* 1999; Meyn *et al.* 2007), however alterations to the landscape such as grazing and farming can reduce biomass and fragment habitat, leading to a reduction in fire occurrence and spread (Marlon *et al.* 2008). Active suppression and fire prevention activities are greater in higher population density areas, largely at the wildland-urban interface, and can also reduce fire frequency and area burned (Cohen 2000; DeWilde and Chapin 2006). As such, fire occurrence tends to be highest at intermediate population and road densities (Syphard *et al.* 2007; Yang *et al.* 2008; Syphard *et al.* 2009; Miranda *et al.* 2011).

Changing fire patterns due to anthropogenic climate change have been linked with increased fire activity in some regions (Gillett *et al.* 2004; Kasischke and Turetsky 2006; Westerling *et al.* 2006; Flannigan *et al.* 2009), longer fire weather seasons globally (Jolly *et al.* 2015) and increases in area burned due to the fuel aridity (Jolly *et al.* 2015;

Abatzoglou and Williams 2016). In many ecosystems fire patterns are predicted to further change with climate change (Krawchuck *et al.* 2009; Westerling *et al.* 2011; Moritz *et al.* 2012; Flannigan *et al.* 2013; Mitchell *et al.* 2014) leading to further declines in biodiversity (Lawson *et al.* 2010; Regos *et al.* 2015), however the direction of the change varies among biomes (Moritz *et al.* 2012; Batllori *et al.* 2013).

1.2 The fire regime

The ecological effects of a fire are discussed in terms of the pattern of immediate and historic characteristics of fires, termed the fire regime (*sensu* Gill 1975). Fire regime encompasses the frequency, intensity, type of fire, and season of occurrence of fires in a landscape (Gill 1975, 1981), the area and patchiness of a fire (Heinselman 1981; Christensen 1993; Gill and Allen 2008), the fire-return interval and the temporal and spatial patterns of fire mosaics (Bradstock *et al.* 2005; Parr and Anderson 2006).

1.2.1 Fire frequency

Fire frequency is a measure of the number of fires occurring per unit time at a given location (Merrill and Alexander 1987). Fire frequency regulates the distributions of many vegetation types in the landscape, e.g., frequent fire limits woody structure in grasslands and savannas (Peterson and Reich 2001; Keeley and Rundel 2005), and closed forests can dominate in areas of low fire frequency (Bond *et al.* 2004). Changes in fire frequency can lead to the switching of the vegetation state of biomes, e.g., flammable vegetation to forested (Baker *et al.* 2020), forests to shrub and grasslands (Ogden *et al.* 1998; Fairfax *et al.* 2009) and fire-sensitive rainforests to degraded forest or savanna (Cochrane *et al.* 1999; Pivello 2011). Too frequent fire can change the structure of the vegetation, leading to landscapes dominated by younger age-classes of trees, which may reduce the abundance and availability of tree hollows (Lindenmayer *et al.* 1991*a*). Hollows that are suitable habitat for fauna have been found to take several hundreds of years to form (Mackowski 1984; Lindenmayer *et al.* 1991*a*; Gibbons and Lindenmayer 1996). Hollow logs on the ground provide important habitat for many species (Bunnell and Houde 2010), and the availability and quality of these habitat resources will also be affected by too frequent fires (Collins *et al*. 2012).

Fire frequency can be viewed as three interconnecting variables, including the time since last fire, the time between fires (inter-fire intervals) and the variability of inter-fire intervals (Morrison *et al*. 1995). The between fire interval and interval variability can influence plant species composition and reproduction (Morrison *et al.* 1995; Taylor *et al.* 1998), fauna species composition (Andersen *et al.* 2005; Smith *et al.* 2013), and habitat availability (Weber and Flannigan 1997; Haslem *et al.* 2012).

1.2.2 Fire intensity and severity

Fire intensity is a measure of the rate of heat release, which is a function of fuel content, fuel consumption, and the rate of spread (Rothermel 1972). Fire severity measures the degree of environmental change caused by fire intensity (Keeley 2009). Fire intensity has direct effects on the survival of individual plants and animals, and indirect effects on fauna via changes in habitat structure (Christensen *et al*. 1981; Smucker *et al.* 2005).

1.2.3 Fire season

Fire season refers to the climatic season (Gill 1975). Fuel moisture content varies among climatic seasons which can affect fire intensity and severity (Govender *et al.* 2006). The season of fire can also affect post-fire responses (Bowen and Pate 1993) and reproduction timing (Taylor *et al.* 1998) in plants, plant community composition (Tsafrir *et al.* 2019), population dynamics and breeding in fauna (e.g., birds: Murphy *et al*. 2010; mammals: Begg *et al.* 1981; reptiles: Greenberg *et al*. 2018), and influences seedling emergence (Ooi *et al.* 2004; Knox and Clarke 2006). Shifts in the timing of fires from early to late in the dry season can influence the intensity of a fire which has been associated with the loss of small mammal biodiversity in northern Australia (Firth *et al.* 2010; Woinarski *et al.* 2010).

1.2.4 Fire patchiness

Fire patchiness refers to the spatial variability in characteristics within a fire, as fires will rarely burn uniformly through an area (Price *et al.* 2003). Fire patchiness will increase as a result of topographic features such as slope and aspect, gullies and rocky outcrops (Keith *et al*. 2002; Price *et al.* 2003; Penman *et al*. 2007) and variations in wind, vegetation type and soil moisture (Anderson *et al*. 2008). Unburnt patches or areas burnt at a lower intensity in the landscape can provide refuge for species during and after a fire and can occur within an individual fire area or at a landscape scale (Penman *et al*. 2007; Robinson *et al.* 2013). Low intensity fires are usually patchier than high intensity fires (Catchpole 2002).

1.2.5 Altered fire regimes

Each of the attributes of the fire regime can influence fire behaviour (Whelan 1995) and as a result, the fire regime is more influential than a single fire event in terms of long-term impacts on a landscape (Wilson *et al*. 2014). Humans have been using fire since pre-historic times, however industrialisation and changes in land use and management have resulted in altered fire regimes from pre-European colonisation in many regions (Veblen *et al.* 2000; Moreira *et al.* 2001; Russell-Smith *et al.* 2007). Anthropogenic-influenced Alterations to fire regimes have caused widespread habitat destruction in fire-reliant habitats throughout the world (Bowman *et al.* 2011, 2013), with over 60 % of terrestrial habitats experiencing altered fire regimes (Archibald *et al.* 2012). Of the fire-sensitive habitats of the world, 70% have experienced altered fire regimes (Shlisky *et al.* 2009) and areas where fire has been rare or absent have recently been burned (e.g., Indonesia, Chisolm *et al.* 2016; South America, Barlow *et al.* 2020; The Arctic, Hu *et al.* 2015). Inappropriate fire regimes are a key threat to almost half (44%) of Australia's threatened species (Evans *et al.* 2011). Altered fire regimes have resulted in a reduction in the extent of many vegetation communities (Gil-Romera *et al*. 2010), reduced species richness in plant communities (Cary and Morrison 1995), reductions in the quantity and quality of habitat (Chia *et al.* 2015), and changes to the relative abundance of species in landscapes (Watson *et al*. 2009; Kelly *et al.* 2011).

Increased urbanisation, increased population density and changes in land use have led to habitat fragmentation and loss and altered fire regimes in many ecosystems (Gill and Williams 1996; Theobold and Romme 2007) in many regions (Underwood *et al.* 2009), leading to declines in biodiversity (Hobbs and Yates 2003). The fragmentation of habitat in urban areas can lead to a reduction in fire frequency due to smaller patch sizes, loss of traditional burning practices or active fire suppression (Cohen 2000; Hobbs and Yates 2003). Conversely, fire frequency can increase due to proximity to ignition sources and land use changes (Sypahrd *et al.* 2007; Chas-Amil *et al*. 2013).

Given the impacts of altered fire regimes, urbanisation, land use, habitat loss, and fragmentation, and the projected increase in fire frequency and severity under future climate conditions (Liu *et al.* 2010), a better understanding of the impacts of different components of the fire regime is urgently needed for biodiversity conservation (Driscoll *et al.* 2010; Kelly *et al.* 2020).

1.3 Fire and biodiversity

1.3.1 Plant responses to fire

Plant species differ in response to fire depending on the characteristics and stage of their life cycle, the fire regime, and post-fire conditions (Gill 1981). The distribution of plants within a landscape depends largely on their ability to survive or regenerate after a fire. Plant mortality is directly linked to the intensity of fire (Burrows 1985; Williams *et al.* 1999), but different morphological and ecophysiological traits will influence which plants survive a fire and survive in the post-fire environment (Keith 2012). Many plants have developed fire-resistant traits (Gill 1981) which enable them to survive fire including thick bark and serotiny (seed storage in cones or fruits; Lamont *et al.* 2020) to protect tissue from heat damage (Burrows 2002), seed storage in the soil (Gill 1981), the ability to re-sprout quickly after fire (Pausas and Keeley 2014), the release of seeds triggered by heat, and germination triggered by smoke and heat (Keeley *et al*. 2011; Simon and Pennington 2012).

Based on these fire-resistance traits, plants generally regenerate after a fire in one of two ways: resprouting (growth from new shoots of surviving tissue or dormant buds) and seeding (growth from a fire-resistant seed bank) (Bell *et al.* 1984; Pausas *et al.* 2004). Re-sprouting species generally survive the fire through protection of growing tissue by thick bark or soil (Bond and Midgley 2001), have the capacity to regenerate from buds or roots (Keeley and Zedler 1978) and are referred to as fire tolerant species (Whelan 1995; Gill 1997). Obligate seeder species are frequently killed by fire but regenerate from seed stored in the canopy or the soil (Bond and van Wilgen 1996) and are referred to as fire sensitive species (Whelan 1995; Gill 1997). However, resprouting and re-seeding are not alternative response mechanisms, and some species exhibit both traits (i.e., facultative seeders; Pausas *et al.* 2004; 2014). Re-sprouting species may also have stored seed from which they can regenerate (Pausas *et al*. 2004).

Species show adaptive traits to a particular fire regime and are at risk under an altered fire regime (Keeley *et al.* 2011). The effects of fire will differ with differing persistence traits. For obligate seeder species (those killed by fire), if intervals between fires is less than the time required to germinate, flower, and produce seed (juvenile period), then the species is at risk of decline or local extinction (Burrows 2008). Conversely, for species requiring fire stimulus for germination, fire intervals exceeding the lifetime of seed stored in a seed bank, may result in a decline in abundance or local extinctions (Bradstock *et al*. 1996; Gill and McCarthy 1998). Altered season of burning can reduce mortality (Jasinge *et al.* 2018), reproductive response or alter the timing of reproduction (Taylor *et al*. 1998). Therefore, changes in the fire regime may result in changes in the species composition of the vegetation via differential effects on individual species related to their specific traits.

1.3.2 Fauna responses to fire

Fire has direct and indirect effects on animals, including mortality either directly from heat or smoke, or indirectly through its influence on habitat or resources; increased predation; behavioural or physiological changes; displacement of individuals or communities; and alterations to the structure and function of habitat. Animals vary in their response to fire, some abandon the area moving ahead of the fire (Christensen 1980), while others shelter from heat generated by the fire in rock crevices, hollow trees, or burrows (Lawrence 1966; Newsome *et al*. 1975; Main 1981; Whelan *et al*. 1996). After fire passes, some species seek refuge in unburnt areas (Recher *et al*. 1975; Begg *et al*. 1981), while others will live or feed in burnt areas (Newsome *et al.* 1975). Some species modify their behaviour to survive post-fire conditions e.g., reducing foraging by increasing torpor (Stawski *et al.* 2015) or using below-ground habitat (O'Donnell *et al*. 2016). Other species will utilise both burnt and unburnt areas for shelter and feeding. Fauna remaining in burnt areas may be more susceptible to predation by other animals due to reduced vegetation cover (Andersen *et al*. 2012; Leahy *et al.* 2016), however some predators may avoid recently burnt areas due to reduced cover (Rochester *et al.* 2010). For some species that favour open conditions fire can have a positive effect (Hutto 2008; Fontaine and Kennedy 2012) by making habitat conditions more favourable for foraging and thermoregulation (e.g., aerial, bark and ground foraging birds (Woinarski and Recher 1997; Bagne and Purcell 2011) and reptiles (Steen *et al.* 2015)). Some species rely on fire to create suitable habitat (e.g., grazing herbivores; Bowman *et al.* 2016).

Direct effects of fire are generally immediate, whereas the indirect effects on fauna occur through the influence on habitat and resources, which can span long temporal scales (Watson *et al.* 2012). Fauna will recolonise an area in response to changes in vegetation structure and density, as their food requirements and nesting and sheltering needs are met (Fox 1982, 1990). Over time, as the vegetation changes and habitats are no longer suitable for a species, they are outcompeted or replaced by other species more suited to the habitat (Fox 1982; 1990; Greenberg *et al.* 1994; Monamy and Fox 2000; Taylor and Fox 2001*a*, 2001*b*; Letnic *et al.* 2004; Sitters *et al*. 2014). This succession pattern suggests that changes in animal communities are driven by changes in habitat attributes. However, the rate at which vegetation recovers after fire can also be influenced by other factors such as temporal variations in precipitation (Monamy and Fox 2000; Letnic and Dickman 2010), the pre- and post-fire climatic conditions (Pastro *et al.* 2011), and fire frequency (Mowat *et al.* 2014) which can affect the resources available to fauna.

1.3.3 Fauna habitat and fire

The term habitat is used to describe the various aspects of where species occur, but descriptions of habitat can be based on: (i) the environmental conditions (living and non-living) that are thought to meet the needs of a taxon; or (ii) the land cover or vegetation type in which a taxon is typically found (Lindenmayer *et al.* 2008*a*). Vegetation structure is described by the attributes (e.g., tree diameter, canopy cover, foliage arrangement, tree height and spacing, plant species, understory vegetation and deadwood; McElhinny *et al.* 2005) and the number and abundance of different attributes present (structural complexity, reviewed in McElhinny *et al.* 2005). Fire plays a key role in determining fauna distribution and abundance across fire-prone landscapes and changes in fire regimes will affect habitat and occupancy of the habitat. The structural attributes of the vegetation are critical determinants of which fauna occupy the landscape as they provide the habitat on which animal species depend directly or indirectly for breeding, shelter and food. Variation in the resilience of species and response to the post-fire environment is related to habitat preferences (Farji-Brener *et al.* 2002; Parr *et al*. 2004; Andersen *et al.* 2007). The rate at which a fire regime alters the abundance of particular habitat characteristics will impact upon species dependent on those resources (Burrows and Abbott 2003).

Habitat components can be affected by the fire regime in different ways. The season of burning affects vegetation structure and composition due to seasonal differences in growth and reproductive stages of species (McLoughlin 1998). Frequent fire can simplify the vegetation structure leading to loss of key habitat attributes and fauna diversity (Catling *et al*. 2001; Huston 2003; Eyre *et al*. 2010; Arthur *et al.* 2012; Aponte *et al*. 2014; Bassett *et al*. 2015). In the longer-term fires that occur too frequently can simplify the structure by reducing shrub and mid-storey plant cover, removing logs, and reducing leaf litter cover (Bradstock 1981; Christensen *et al*. 1981; Fox and Fox 1987;

Tasker and Dickman 2004) and may cause declines in fauna species (Woinarski *et al.* 2010), particularly small mammal species that are sensitive to fire (Andersen *et al.* 2005). Human land uses (grazing, forestry and clearing for development) combined with fire can further alter vegetation condition and can simplify vegetation structure (Foley *et al.* 2005).

High intensity fires can lead to greater mortality of fauna (Recher *et al*. 1975; Newsome and Catling 1983). Large fires that exceed the home ranges of animals can lead to declines in local populations (Lawes *et al*. 2015) and the impacts on animal populations can be further exacerbated by interactions with indirect effects such as predation after the fire (Andersen *et al.* 2012; McGregor *et al.* 2016).

The severity of a fire will vary spatially in the landscape, due to variation in fire behaviour led by environmental gradients such as fuel and surface moisture and topography, vegetation, weather conditions, the amount and arrangement of fuels, and fire history (Hammill and Bradstock 2006; Schoennagel *et al.* 2008; Holden and Jolly 2011; Leonard *et al.* 2014). Variation in fire severity can increase heterogeneity in fire-prone landscapes (Burton *et al.* 2008; Schoennagel *et al.* 2008), driving important ecological and successional processes (Turner *et al.* 1998), and the creation of un-burnt refuges (Robinson *et al.* 2013).

Refuges in the landscape are important for the provision of shelter and resources (Fraser *et al.* 2003; Garvey *et al.* 2010; Banks *et al.* 2011; Shaw *et al.* 2021). Some habitat attributes will be less affected by fire (e.g., rock outcrops, logs) and can provide refuge for fauna during the passage of fire (Robinson *et al.* 2013). Refuges can also be patches of vegetation with a higher moisture content than the surrounding vegetation (e.g., riparian areas, gullies, or patches of rainforest) and can burn less frequently or severely (Bowman 2000; Penman *et al.* 2007). Changes in the fire regime (e.g., too frequent, or high intensity fires) can result in these areas burning as severely as the surrounding landscape (Leonard *et al.* 2014), leading to homogenisation of habitat and a reduction in refuges.

Many studies have examined the response to fire of species, taxonomic groups and vegetation communities (e.g., Vertebrates: Newsome *et al*. 1975; Recher *et al*. 1975; Christensen 1980; Trainor and Woinarski 1994; Woinarski and Recher 1997; Sitters *et al*. 2014; Invertebrates: York 1999, 2000; Arid landscapes: Letnic, 2003; Letnic *et al*. 2004; Heathland: Main 1981; Fox, 1982, 1990; Whelan *et al*. 1996; Monamy and Fox, 2000; Woodlands: Valentine *et al*. 2012), the impacts of fire regimes on species or group of species (e.g., Braithwaite 1987; Bradstock *et al*. 2005; Burrows 2008), and the impacts of the various components of the fire regime (e.g., time since last fire: Coops and Catling 2000; Catling *et al.* 2001; Smucker *et al.* 2005; Watson *et al*. 2012; fire frequency and interval: Andersen *et al.* 2005; Haslem *et al.* 2011; fire intensity: Abbott 1984; season of burning: Griffiths and Christian 1996). Most of these studies though, have focused on one aspect of the fire regime (e.g., time since fire) or a small number or species.

However, the combined effects of multiple fire regime components have been shown to strongly influence biodiversity, including fire severity and time since fire (Hutto and Patterson 2016; Roberts *et al.* 2020), inter-fire interval (Morrison *et al.* 1995; Haslem *et al.* 2012; Aponte *et al.* 2014; Fairman *et al.* 2016), size, severity, and frequency (Lawes *et al.* 2015), and the spatial patterns of overlapping fires (Sitters *et al.* 2014; Sollmann *et al.* 2016).

1.3.4 Key habitat attributes and fire

Key structural attributes found to promote the persistence of fauna in forests and woodlands include mistletoe, timber debris, cavities or hollows in trees or logs, leaf litter, bark, and ground, shrub and canopy cover (McElhinney *et al.* 2006). Mistletoe have been described as a keystone resource in forests and woodlands because of their importance to a range of species as a source of food and nesting habitat (Watson 2001*b*) and are associated with increased species richness and resource availability (Watson *et al.* 2009). Most mistletoe species are sensitive to fire (Kipfmueller and Baker 1998; Start 2015) and changes in the size, severity and frequency of fires can reduce mistletoe abundance (Start 2015; Ritter *et al.* 2018).

Coarse woody debris including logs and branches provides habitat for a wide range of vertebrate and invertebrate taxa (Freedman *et al.* 1996; McComb and Lindenmayer 1999). A reduction in the abundance and quality of logs and coarse woody debris by too frequent fire can result in habitat loss for small mammals and reptiles (Spies *et al*. 1988; Catling 1991; Webster and Jenkins 2005; Croft *et al.* 2010). For example, areas of frequently burnt forests have been found to contain fewer logs with hollow and fewer hollows in than areas with a longer time since fire (Collins *et al.* 2012; Croft *et al.* 2016).

Hollows in trees and logs are key habitat for a large number of species (Gibbons and Lindenmayer 2002), and their requirements for hollows differs among species (Goldingay 2009, 2012). Hollows are formed as a natural part of the decaying process after limb loss or fire and can take 100-300 years to form in Australia (Wormington *et al.* 2003). Fire can increase the abundance of hollows in the landscape due to scarring (Inions *et al.* 1989), however frequent and high intensity fire can burn hollow trees, reducing the abundance and quality of hollows in the landscape (Inions *et al.* 1989; Eyre *et al.* 2010).

Bark and leaf litter are important habitat features for a range of invertebrate, bat, reptile, and small mammal taxa (Claridge and May 1994; Majer *et al.* 2001; Lumsden *et al.* 2002; Wilson and Swan 2003). Fire can reduce the litter layer and bark on trees (Tolhurst *et al.* 1992) reducing shelter and food resources. Frequent fire can lead to a reduction in litter decomposition rates by changing the composition of soil fungal communities (Holden *et al.* 2013), altering invertebrate-fungal relationships (Brennan *et al.* 2009), and decreasing litter moisture content due to increased aridity through the removal of the understorey (Raison *et al.* 1986). Frequent low intensity fire can reduce species richness of litter-dwelling invertebrates (York 1999) and the impacts of fire on the abundance and diversity of species can vary with season (Campbell and Tanton 1981; Vasconcelos *et al.* 2009). Litter-dwelling fungi and invertebrates are an important food source for many vertebrate species (Vernes and Dunn 2009) and the recovery of vertebrate fauna may be linked with the recovery of litter. High severity fire can completely incinerate bark and leaf litter, leading to reductions in abundance and richness of litter-dwelling invertebrates (Buckingham *et al.* 2019), local invertebrate extinctions (Rodrigo *et al.* 2008), and loss of habitat.

The ground, shrub and canopy layers of the vegetation provide crucial shelter, nesting, roosting and feeding habitat for fauna (MacArthur and MacArthur 1961; Major *et al.* 2001; Fischer *et al.* 2005; Debus *et al.* 2006). Fire will initially simplify the vegetation structure through direct consumption of plant biomass and change the spatial and temporal dynamics of vegetation (Bond and van Wilgen 1996). Fire can also increase structure complexity by the post-fire germination and resprouting of plants (Gill 1975). Frequently burnt or long-unburnt vegetation can become dominated by selected plant species at the expense of others (Bradstock *et al.* 1996; Lunt 1998).

1.4 Managing landscape with fire

A common strategy in fire management for biodiversity conservation is to maintain patches of differing fire histories within a landscape (pyrodiversity), known commonly as patch mosaic burning (Saxon 1984; Parr and Brockett 1999; Brockett *et al.* 2001; Bradstock *et al*. 2005; Parr and Andersen 2006; Spies *et al*. 2012). A mosaic of differing times since fire is considered important as species differ in their response to fire and depend on resources that vary temporally with differing times since fire (Fox, 1982; Kelly *et al*. 2015). A heterogeneous mosaic of different fire histories across space and time will ensure diversity in habitat in a landscape, facilitating persistence of a greater diversity of biota (Bradstock *et al.* 1995; Edwards *et al*. 2001; Burrows and Wardell-Johnson 2003; Parr and Andersen 2006).

Evidence to support patch mosaic burning comes from studies in a range of environments (Masters 1993; Woinarski *et al.* 1999; Letnic and Dickman 2005; Fuhlendorf *et al.* 2006). Positive relationships between heterogeneity in habitat and species diversity have been shown across many taxonomic and functional groups and at differing spatial scales (MacArthur and MacArthur 1961; Tews *et al.* 2004; Stein *et al.* 2014) and many species require a mosaic of fire histories in their home ranges (e.g., Woinarski and Recher 1997; Firth *et al.* 2010; Andersen *et al.* 2012). However, in some instances, heterogeneity in habitat resulting from pyrodiversity has had no or even a detrimental effect on biodiversity (e.g., Sutherland and Dickman 1999; Beckage and Stout 2000; Driscoll and Henderson 2008; Lindenmayer *et al.* 2008*b*; Kelly *et al.* 2010).

More recent research has moved to a more strategic approach to fire management, to determine the ideal ratio of vegetation age classes at a landscape level, based on known fire responses of biota (Davies, *et al*. 2012; Kelly *et al*. 2012; Nimmo *et al*. 2013). Each vegetation age class represents the time since last fire, where different resources (such as nutrients, shelter and food resources) are provided with different age classes (Di Stefano *et al*. 2013).

However, the post-fire recovery of vegetation and habitat will also be influenced by the legacies of previous fires (Catling 1991; Gill and Catling 2002). Previous fires will vary in size and timing and, when overlain by later fires, create a complex pattern of patches of differing fire history and vegetation structure in the landscape (Avitable *et al.* 2013). Vegetation responds differently to fire spatially and temporally and at multiple scales (Pastro *et al.* 2013), influenced by fire history, rainfall gradients (Davies *et al.* 2012) and interactions with other processes affecting vegetation structure (e.g., herbivores; Staver *et al.* 2009). This can lead to geographic variation in the post-fire responses of fauna (Driscoll *et al.* 2012).

The broad, blanket approaches of these strategies are limited by a lack of detailed knowledge of appropriate fire regimes for most fauna species (Bradstock and Cohn 2002; Clarke 2008). The response of many fauna species to fire, and the characteristics of the fire regime necessary for animals to persist are mostly poorly understood (Bradstock and Cohn 2002; Clarke 2008). Fire regimes are often implemented with the assumption that the needs of fauna will be met through plant diversity (Clarke 2008; Driscoll *et al*. 2010). Thus, a key challenge is defining the appropriate fire regime that provides adequate resources for the conservation of biodiversity.

1.4.1 Prescribed fire as a management tool

The south-east of Australia is one of the most fire-prone areas in the world (Dwyer *et al*. 2000; Russell-Smith *et al*. 2007) with most ecosystems having some level of reliance on fire (Singh *et al*. 2002; Andersen *et al*. 2005). Much of the vegetation in Australia has evolved with fire (Fox and McKay 1981; Singh *et al*. 1981) and many species of Australian fauna show fire-adapted traits (Sutherland and Dickman, 1999).

Fire has been applied purposely to the landscape in Australia for up to 65 000 years (Clarkson *et al.* 2017), beginning with Indigenous Australians using fire to manipulate landscapes to minimise the risk of wildfire and to improve hunting and access through the landscape (Nicholson 1981; Bowman 1998). Prescribed burns are still applied to the landscape for wildfire management, life and property protection, agricultural and forestry practices, and to conserve biodiversity (Whelan 1995; Tran and Wild 2000; Andersen *et al*. 2005; Bartlett *et al*. 2007; Morgan *et al.* 2020). Land management agencies are generally required to protect life and property from fire as a first priority. The extent and severity of wildfire can be reduced through prescribed burning to reduce fuel loads in the landscape (Fernandes and Botelho 2003; Morgan *et al.* 2020), in combination with the active suppression of wildfires. In Australia, prescribed burning is also used to achieve conservation goals, such as maintaining biodiversity (Bradstock *et al.* 1995; Richards *et al.* 1999; Haines *et al*. 2001).

1.4.2 Burning for hazard-reduction objectives

Recent large-scale wildfires in south eastern Australia (including the 2003 and 2005 fires in the Alpine region, the 2003 Canberra fires, the 2004, 2013, 2019-20 NSW fires and the 2009 Victorian fires) and the associated loss of lives and properties have placed the fire management practices of land managers in the spotlight (Clarke 2008), with calls to increase the amount of prescribed burning for hazard reduction undertaken each year (Teague *et al*. 2010).

Prescribed burns to reduce hazardous fuel loads (hereafter hazard-reduction burns) are carried out with the primary goal of reducing the risk of wildfire to human lives and infrastructure. These burns are generally low-intensity fires with a flame height of up to 1 metre, designed to reduce the fuel loads in an area (Gill *et al*. 1987; McCarthy *et al*. 2001;

Whelan 2002, 2009). The trigger for hazard-reduction burning is when the fuel loads reach defined levels, for example around 15 t ha-1 in some forests (McCarthy 2002).

Hazard-reduction burns are generally concentrated around the rural-urban interface, as they are more effective at reducing the intensity of wildfires than active suppression (Price and Bradstock 2011), and thus more effective in supporting safe evacuation and protection of property (Price and Bradstock 2012). These burns are typically undertaken in mild weather conditions to create low-intensity, manageable fires (Penman *et al*. 2011). Prescribed burning however, involves many uncertainties. The effectiveness of prescribed burning in reducing the risk of wildfire is limited and dependent on climatic factors such as temperature and rainfall (Bradstock *et al*. 2012), and the impacts on ecosystems can be complex (Altangerel and Kull, 2013).

1.4.3 Burning for ecological objectives

Prescribed burning where the primary objective is the conservation of biodiversity (hereafter ecological burns) are one tool used to minimise risk of species extinctions (Bradstock *et al*. 1995). As life and property protection are not the primary goals, the timing of burns can be manipulated to promote specific responses of biota and can be applied at a variety of scales and arrangements to suit different objectives (Whelan 1995). Ecological burns are typically low intensity burns which can result in patches of un-burnt micro-habitats that can provide refuge for fauna during a fire (Andrew *et al*. 2000). Low intensity, patchy burns can reduce the incidence of high intensity wildfires thereby leading to an increase in abundance and diversity in some species following the fire (Sitters *et al.* 2015; Radford *et al.* 2020).

Given the importance of pyrodiversity in the landscape for the persistence of many species (Bradstock *et al*. 1995; Edwards *et al*. 2001; Burrows and Wardell-Johnson 2003;

Parr and Andersen 2006), and the impact to ecosystems from the departure of historical fire intervals (Lunt 1998; Pausas 2009), designing and implementing ecologically sustainable fire management is key for conserving biodiversity in any landscape. Fire return intervals, which guide the targets for proportions of the landscape in any given state, can be calculated in a number of ways including fuel biomass (e.g., South Africa: Brockett *et al.* 2001; van Wilgen *et al.* 2008), natural fire intervals and age class distributions (e.g., Sweden, Angelstam 1998; Australia: Woinarski and Winderlich 2014), or flora life history traits and responses to fire (e.g., Australia: Watson 2001*a*; Burrows and Abbott 2003). Prescribed burning programs to maintain biodiversity have been implemented in a range of ecosystems across the world including forests (Burrows and McCaw 2013), grasslands (Van Dyke *et al.* 2004; Clark *et al.* 2020; Radford *et al.* 2020), and heathlands (Ascoli *et al.* 2009; Murphy *et al.* 2015).

However, these programs are generally based on managing vegetation and rarely make reference to considerations for fauna (Clarke 2008; MacHunter *et al*. 2009; Fontaine and Kennedy 2012), largely due to a lack of ecological knowledge on the needs of fauna in regard to fire (Bradstock and Cohn 2002; Clarke 2008). The responses of plants and animals to fire are complex, due to the interactions between attributes of the fire (intensity, extent, and season of burning), fire history, habitat conditions, landscape attributes and climatic factors including rainfall and drought (Gill 1981; Whelan 1995). Fire intervals derived from the fire response of one plant species fail to consider important elements such as fire intensity and the legacies of historic fires (Driscoll *et al.* 2010). This may result in outcomes not suitable for all species, including other taxa (Clarke 2008).

Moreover, habitat attributes such as tree hollows and decaying logs may take longer to develop than the time frames needed for plant reproduction and survival (Driscoll *et al*. 2010; Di Stefano *et al*. 2013). Key habitat attributes for many fauna species such as tree hollows, fallen logs and dense cover are thought to be more abundant in long-unburnt vegetation (Harmon *et al*. 1986; Kenny *et al.* 2003; Croft *et al.* 2016) and long unburnt habitat has been found to be disproportionately important for some species (Kelly *et al.* 2012; Taylor *et al.* 2012; Nimmo *et al.* 2013).

1.4.4 Guidelines for ecological burning in New South Wales

One way of estimating appropriate fire regimes for flora is based on functional life-history traits of species relating to responses to fire (Noble and Slatyer 1980; Gill 1981; Pausas 1999). Noble and Slatyer (1980) defined the most important groups of vital attributes of plant species for response to disturbances such as fire as: "(i) method of arrival or persistence at the site during or after a disturbance; (ii) ability to establish and grow to maturity after fire; and (iii) time taken to reach critical life stages". With fire return times outside these intervals species declines can be expected (Richardson *et al*. 1994; Pausas *et al*. 2004; van Wilgen *et al*. 2011; Di Stefano *et al*. 2013).

Current ecological fire management within NSW National Parks is based on a framework of recommended minimum and maximum fire intervals required for vegetation groups to maintain plant diversity (Kenny *et al*. 2003; Bradstock and Kenny 2003). The minimum fire-interval is based on the most fire-sensitive species in the vegetation type (Di Stefano *et al*. 2013). Fire-return intervals are applied at a scale based on the NSW vegetation classification system that groups vegetation into broad categories of formations (Kenny *et al.* 2003; Keith 2004).

However, variations in fire regimes have been shown to be strongly associated with local topography, climate (Beaty and Taylor 2001; Hellberg *et al.* 2004; Flatley *et al.* 2011), soil and geological features (Fensham and Kirkpatrick 1992; Keith 2011). Broadly categorised land cover types will not always reflect the amount of suitable habitat for particular animals. A large area of forest, for example, may not be suitable habitat for forest-dependent animals due to the lack of old-growth necessary to provide critical habitat, such as hollow logs and hollows in trees (Lindenmayer and Franklin 2002).

1.5 Fire History

Accurate fire histories are important for land management, strategic fire planning, and ecological research (Hardy *et al.* 2001; Whelan 2009; Driscoll *et al.* 2010). Fire data are used to prepare for wild and prescribed fires, allocate resources, forecast fire danger (McArthur 1966,1967), and model changes in fire behaviour due to climate change (Bradstock *et al*. 2012).

Given the deleterious effects of inappropriate inter-fire intervals on plants, animals, and habitat (Cary and Morrison 1995; Morrison *et al.* 1995; Bradstock *et al.* 1997; Andersen *et al.* 2005; Haslem *et al.* 2012), knowledge of the attributes of the fire regime in a given area is critical to understanding how fire regimes affect biodiversity (Morgan *et al.* 2001; Driscoll *et al*. 2010).

Fire records are generally stored in written format, or spatially in Geographical Information Systems (GIS) and reliable and comprehensive fire history data can allow for the evaluation of patterns including frequency, severity, ignition type, and area burnt (Morgan *et al.* 2001; Wittkuhn and Hamilton 2010). However, accurate fire history records are poorly known for many regions (Whelan 2009; Short 2014), and rarely contain data on all aspects of the fire regime such as patchiness and severity (Srivastava *et al.* 2013; Russell-Smith *et al.* 2017).

Error is inherent in spatial data, and common sources of error in spatial datasets include incompleteness of records, repeated records, locational bias, and missing records (Kasischke *et al.* 2002; Kraaij *et al.* 2013; Short 2014; Syphard and Keeley 2016).

Inconsistencies in the amount and type of error in datasets may arise due to sampling bias, uneven collection effort (Yang *et al.* 2013), or data being combined from different sources (Sheeren *et al.* 2009). Unreliable fire history has the potential to impact on the interpretation of fire history, limiting the use of fire history data for analyses of long-term responses of biota to fire regimes (Syphard and Keeley 2016).

1.6 Objectives of this thesis

This thesis is an examination of fire history and fire management in the context of fauna conservation in NSW, Australia. Initially, I asses how the quality of data may affect the interpretation of fire history, then I identify sources of error in the database. Subsequently, I test whether distributions of time since fire for different vegetation types follow predicted trends at varying scales and identify the degree to which distributions of time since fire are influenced by landscape management actions. Finally, I examine the relative influence of time-since-fire, inter-fire interval, environmental and abiotic factors, and vegetation type on fauna habitat at a fine scale. A summary of the key objectives of this project is outlined below.

Chapter Two

Chapter two is a general methods chapter which outlines the study site and a detailed description of the methods used in each subsequent chapter. This chapter also details the pilot study undertaken to finalise the layout and methods for the field work component of this thesis. Chapters three to five were prepared as individual papers and there is some repetition of the study site and methods in these chapters.

Chapter Three

Fire records for NSW are contributed to by multiple fire agencies and exist in multiple datasets. In this chapter I describe the process for the integration of multiple datasets and the steps undertaken to identify and merge replicate records. I examine how the quality of the data may affect interpretation of fire history for biodiversity conservation. I use a novel approach to examine trends in the database over time and compare multiple methods of change point analyses.

Chapter Four

Variations in fire regimes have been shown to be strongly associated with local topography, climate (Beaty *et al.* 2001; Hellberg *et al.* 2004; Flatley *et al.* 2011), soil and geological features (Fensham and Kirkpatrick 1992; Keith 2011). This chapter examines the extent to which distributions of time since fire in different vegetation types and at different scales follow predicted patterns. I examine the relative influence of land management actions on distributions of time since fire.

Chapter Five

Variations in combinations of fire severity and inter-fire intervals impact vegetation structure, composition, and therefore habitat differently (Steel *et al.* 2021). In this chapter I used a field-based study to investigate the impacts of fire history, vegetation type, and environmental factors on habitat attributes, and the extent to which they vary among vegetation types.

Chapter Six

In this chapter I present a summary of the main findings and discuss their implications for management for biodiversity conservation. I make specific recommendations for fire management for the conservation of fauna and fauna habitat, and directions for further research.

Chapter 2 Study area and general methods

My study had two components; Part 1 was a desktop Geographical Information Systems (GIS) analysis of the fire history of New South Wales (NSW), and Part 2 was a field-based study of habitat attributes in relation to vegetation type and fire history. The second component used the results of the first component to select field sites. In this chapter, I have expanded on the details of the methods given in Chapters 3, 4, and 5. In those chapters, these methods appear more as they would in a publication. Some of the descriptions of methods here remain very similar to that appearing in Chapters 3, 4, and 5, and are repeated here just to provide context to the surrounding methods.

2.1 Study Area

My study area was the State of New South Wales (NSW), occupying 80.1 million ha in south-eastern Australia. Geographically, NSW is divided into three regions: a thin, coastal strip in the east with a length of 2137 km; the Great Dividing Range, a complex of mountain ranges, escarpments and plateaus running parallel to the coast, ranging in width from 50 to 160 km and in elevation from 300 to 2228 m; and the low, western plains, which cover almost two-thirds of the State.

The climate of NSW is spatially and temporally variable. In the mesic east the climate varies from north to south. The southern climate is cool with uniform rainfall through the year (mean annual rainfall 600-1500 mm). The northern climate is humid and sub-tropical with high summer and low winter rainfall (mean monthly rainfall winter 200-400 mm, summer 400-800 mm; Bureau of Meteorology 2020*a*). The Great Dividing Range enhances rainfall near the coast and contributes to the main environmental gradient running from the temperate east (mean annual rainfall 600 - 2000 mm, warm summers and cold winters, mean annual temperature range 9 – 24^{o}C) to the semi-arid and arid west (mean annual rainfall 100 - 500 mm, hot dry summers and cold winters, mean annual temperature range 12 – 27^{o}C) (Bureau of Meteorology 2020*a*, *b*). The alpine and sub-alpine regions of the Great Dividing Range in southern NSW experience high winter precipitation and dry summers (mean annual rainfall 1000-2000 mm, mean annual temperature range 6 – 12^{o}C) (Bureau of Meteorology 2020*a*, *b*).

2.1.1 Vegetation

Areas mapped as extant vegetation in 2010 (49.5 million ha, 62% of NSW) were used in Part 1 of my study, and any areas mapped as cleared were excluded (30.6 million ha) (Keith and Simpson 2010). The extant vegetation of eastern NSW is dominated by wet and dry eucalypt forests, with a small area of alpine and sub-alpine vegetation in the south-east, and small areas of rainforests scattered down the east coast, predominantly in the north east. West of the Great Dividing Range vegetation is comprised largely of grasslands, open woodlands and arid shrublands (Groves 1994).

Extant vegetation of NSW is classified based on structure and physiognomy into ten formations, of which four are divided into two sub-formations (hereafter formations and sub-formations are referred to as formations) (Keith 2004; Table 2.1). The 16 formations are further subdivided into 103 classes based on shared structural and floristic characteristics (Keith and Simpson 2010; Table A2.1). Of the 103 classes, seven had <42 ha of fire recorded, or only had fire records for one or two years and were not used in analyses. These formations and classes are the ‘vegetation types’ of my study. Each vegetation type was classified as eastern, western, or widespread (Table 2.1). Eastern vegetation types had >90% of their area east of the western edge of the Great Dividing

Range and western vegetation types had >90% of their area west of the western edge of the Great Dividing Range). Widespread vegetation types occur in both eastern and western NSW (Table 2.1) and were excluded from all east/west comparisons. Vegetation types were further classified as wet based on mean annual rainfall exceeding 900 mm or being dominated by plant species tolerant of periodic inundation or waterlogging (Keith 2004). Vegetation types not meeting this definition were classified as dry.

Except for Alpine and Heathlands, the formations span between 0.5 and 8.8 million ha of NSW. The arid and semi-arid western formations each span a large range and combined they range from ~800 km from the western border of NSW to almost the western edge of the Great Dividing Range. Three of the four extend approximately 500 – 700 km from the northern to southern borders of NSW. The eastern formations are more restricted within the eastern third of the State, however all but the Alpine formation extend the approximately 950 km from the northern to the southern border.

2.1.2 Land managed for biodiversity conservation

The NSW National Parks and Wildlife Service (NPWS) is responsible for over 7 million hectares (9% of NSW) of land within NSW (Figure 2.1). NPWS Estate land was used in both parts of my study for exploring fire history in areas managed for biodiversity conservation. NPWS Estate land was used in Part 1 of the study for comparing the quality of fire records and fire history in areas managed for biodiversity to those not. The field work for Part 2 of the study was carried out within NPWS Estate land.

Authorities use a zoning system to set fire management objectives across NSW; lands where asset protection is not the primary objective, and a key use of fire is to promote ecological outcomes such as biodiversity conservation, are termed Land Management Zones (LMZs) (Office of Environment and Heritage 2013). Approximately

9.5% of NSW is set aside as formal reserves, and approximately 10% of privately-owned land is managed for conservation (NSW Environment Protection Authority 2018).

Although LMZs occur in these and other tenured land, here only the 6.5 million ha (14% of extant vegetation) zoned as LMZs in NPWS land (NPWS LMZ) were used.

Within NPWS LMZs, guidelines for fire management of vegetation formations aim to ensure that each vegetation formation has a range of post-fire ages aimed at minimising the loss of vascular plants and threatened fauna (Kenny *et al*. 2003). These guidelines identify for each formation/sub-formation: a minimum interval, the shortest inter-fire interval to avoid localised decline or loss of species due to too frequent fire; and a maximum interval, a predicted time since fire beyond which senescence of plants and stored seed can lead to plant species loss. It is recommended that at least 50% of a formation has times since last fire between the minimum and maximum intervals, less than 35% below the minimum interval, and less than 35% above the maximum interval (Kenny *et al*. 2003; Office of Environment and Heritage 2013). Four vegetation formations have the recommendation that deliberate burning should be avoided: Alpine, Arid Shrublands (Chenopod sub-formation), Rainforests and Saline Wetlands (Kenny *et al*. 2003). Whilst the recommended intervals in NSW are implemented at a formation level and not at the class level, here I have not differentiated between formations and classes and applied the recommended intervals for each formation to the classes within.

Table 2.1. Vegetation formations and classes in New South Wales (NSW) and National Parks and Wildlife Service Estate

For each formation or sub-formation: number of classes; abbreviation used in the thesis (Abbr.); located (Loc.) predominantly in eastern NSW (E), western NSW (W) or widespread through NSW (X); moisture level (Moist.): dry (D) or wet (M); total area and percent with fire records for NSW; area within NSW National Parks and Wildlife Service Estate Land Management Zones (NPWS LMZ) and percent with fire records; percent of area not within NPWS Estate (non-NPWS) with fire records; and maximum number of years since the most recent fire.

Formation/sub-formation [# classes]	Abbr.	Loc./ Moist.	Total area NSW (Mha)/ [% with fire records]	Total area NPWS LMZ (Mha)/ [% with fire records]	% non-NPWS with fire records	Max. years since fire
Dry Sclerophyll Forest (Shrubby) [14]	DSFS	E/D	4.868 [63]	1.867 [86]	50	92
Dry Sclerophyll Forest (Shrubby/Grassy) [10]	DSFG	E/D	2.762 [41]	0.724 [70]	31	92
Grassy Woodlands [7]	GrWd	E/D	1.897 [30]	0.328 [78]	20	81
Heathlands [7]	Heat	E/D	0.174 [77]	0.109 [90]	55	81
Alpine [4]	Alp	E/D	0.152 [88]	0.135 [90]	69	79
Wet Sclerophyll Forests (Grassy) [5]	WSFG	E/M	1.771 [60]	0.576 [76]	52	92
Wet Sclerophyll Forests (Shrubby) [4]	WSFS	E/M	1.357 [60]	0.512 [70]	54	92
Rainforests [9]	Rain	E/M	0.551 [35]	0.311 [35]	35	92
Semi-arid Woodlands (Shrubby) [9]	SASh	W/D	11.601 [29]	0.685 [60]	27	67
Arid Shrublands (Acacia) [4]	ArAc	W/D	8.842 [6]	0.306 [18]	6	44
Arid Shrublands (Chenopod) [3]	ArCh	W/D	6.968 [3]	0.407 [5]	3	44
Semi-arid Woodlands (Grassy) [5]	SAGr	W/D	4.755 [6]	0.266 [5]	6	67
Grasslands [6]	Gras	W/D	1.337 [3]	0.055 [24]	3	80
Freshwater Wetlands [7]	FreW	W/M	1.349 [6]	0.074 [42]	4	80
Forested Wetlands [5]	ForW	X/M	1.014 [19]	0.179 [41]	14	81
Saline Wetlands [47]	SalW	X/M	0.073 [13]	0.017 [24]	9	80

2.2 Fire history data

The fire history data to informs Parts 1 and 2 of my study were drawn from digitally stored data, managed by the key fire management agencies in NSW. Other sources of fire records have the potential to inform our understanding of fire history, but it was beyond the scope of this thesis to explore these. The digital data used here were the most appropriate to meet my research aim of exploring fire history in relation to biodiversity management; these data are the key resource used to inform biodiversity and fire management decisions in NSW.

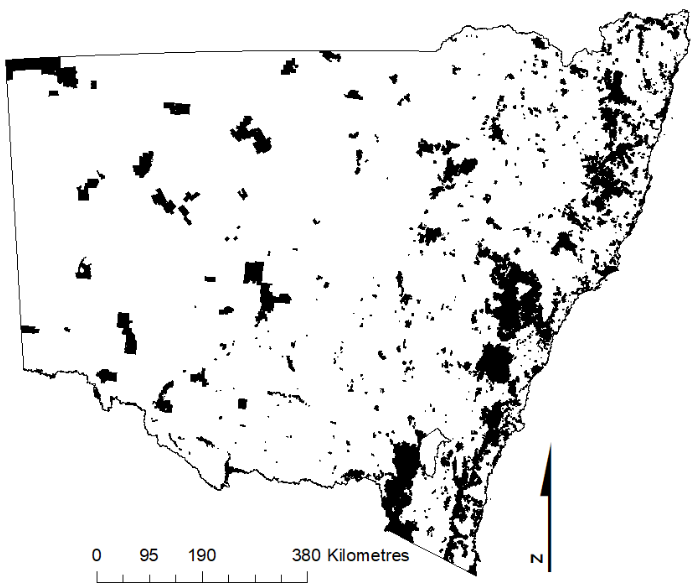


Figure 2.1 New South Wales National Parks and Wildlife Service tenured lands which are classified as Land Management Zones

2.2.1 Data sources

For the GIS studies that are reported in Chapters 3 and 4, and for selecting the field study sites reported in Chapter 5, I used all fire records for NSW, which were stored within four digital datasets, three managed by the NSW Rural Fire Service (NSW RFS) and one by the

NSW Office of Environment and Heritage (OEH; now Department of Planning, Industry and Environment).

Fire records in the datasets are contributed by four main agencies responsible for fire management in vegetated areas of NSW: (i) the NSW Rural Fire Service (NSW RFS) with fire management responsibilities for approximately 95% of the state; (ii) NSW Fire and Rescue Service, responsible for vegetated areas within urban and regional centres; (iii) NSW National Parks and Wildlife Service, within NSW Department of Planning, Industry and Environment , responsible for fire management within 7 million hectares of land; and (iv) NSW Forestry Corporation, responsible for 2.2 million hectares.

Data in all four datasets are stored in GIS layers as spatial records of reported incidences of wildfires, planned fires or mechanical hazard reduction. The NSW RFS maintains the central fire database that is the primary source of fire data for wildfire management across NSW.

At the time of the study one NSW RFS dataset (abbreviated as RFS_WF1) contained wildfire records from 2001-2018, the second (RFS_WF2) contained wildfire records from 1902-2007, and the third (RFS_HR1) contained hazard reduction records from October 2006 to February 2016. The NPWS dataset (NPWS_F) contained fire records from 1902 – 2016 within NSW National Parks and Wildlife Service Estate (Table 2.2).

Each record in the datasets represents an individual wild or prescribed fire. The four datasets contained information for the attributes: fire name or label; fire type (prescription or wild); year of fire; fire season; start and end dates of the fire; cause (e.g., lightning, campfire, equipment use, undetermined); data capture method (thermographic camera, satellite data, GPS airborne, GPS car, hand drawn or unknown); data source (agency or department who supplied data); fire size (area), fire perimeter length; branch or division of RFS that responded to the fire; and the management area within which the fire occurred. Eight of the eleven attributes in the RFS and NPWS_F datasets relevant to these analyses were used (Table 2.3). The remaining attributes were only useful to the agency (e.g., objective met). Not all records contained information for all attributes. For each record in each original dataset a unique identifying number ‘Record ID’ was assigned that linked it to the original dataset and record. If records did not have a value for year of fire, a single calendar year was assigned to the records based on start or end date. If there was no date, the earlier of the two calendar years recorded for season was used. Thus, for fires with no start or end date, the wrong year may have been assigned e.g., fire season 2002 - 2003, fire year assigned as 2002 but fire occurred in 2003. The four datasets were then projected using GDA94 (NSW Lambert Projection) coordinates and the fire size (area) and fire perimeter length were recalculated.

2.2.2 Data cleaning

Prior to any analyses, a three-step cleaning process was undertaken. As a first step to producing a complete list of recorded fires for NSW, an initial clean of each of the four datasets removed any record which was not a fire or with insufficient information in the attributes to determine whether it was a fire record. The RFS_HR1 dataset included non-fire management actions; the 82 443 records that contained the words ‘mechanical, ‘chemical’, ‘grazing’, ‘slashing’ or ‘other’ in the method column of the attributes table were removed so only records containing the word ‘burn’ were retained. The 2605 records (totalling 81 861 ha) in the RFS_HR1 dataset that had no attribute information were removed, as these records could not be used in analyses. The 1841 fire (total of 0.4 ha) records <10m^2 were also removed as it was unable to be determined if they were fire suppressed quickly, pile burns of collected debris, or a data entry error (Table 2.2).

The second step was an automated clean using tools in ArcMap (ESRI 2013) to identify replicate records. Fire Name and Fire Year were used in the 'Find Identical' tool to find replicated records within a data set. These deleted records were visually checked to ensure they were replicates of a retained record. The 'Are Identical To' option within the 'Spatial Join' tool was then used to compare to find any records with identical fire year, area (ha) and perimeter (m) between data sets. The polygons for each record identified by the ArcMap tools were visually checked and repeat records of the same fire were removed, whilst retaining all attribute information if spread among multiple records. The four cleaned datasets were then merged into one database (hereafter database (*a*)).

The final step was a manual-clean of database (*a*) where records were sorted alphabetically by fire name and then year.

Then, after a visual inspection, any polygons with the same fire name and year and overlapping perimeter were merged. Most fires in database *(a)* did not have a fire name, so all records were sorted chronologically then each record was selected, and the information icon used to identify multiple layers of records with the same year and the same or similar area and perimeter size. Any records matching these criteria were merged into one record, resulting in the creation of a new boundary that covered the maximum possible area for all records of that fire. As some of the boundaries were slightly different this process may have inflated the area burnt for some records. Most records did not have information on season or month of fire so this process may also have merged fires that occurred at different times in the same year and in the same area. These criteria for merging may not have recognised replicate records of small fires which were recorded with different coordinate systems or datums and did not overlap. Database (*a*) contained 36 176 unique records of fires in extant vegetation from 1902 to 2018.

Fire management varies among the 16 native vegetation formations, based on structure and physiognomy (NSW Rural Fire Service 2021). GIS layers of the vegetation formations of NSW (version 3.03, Keith and Simpson 2010) were used to create 16 separate subsets of database (*a*) for each vegetation formation within NSW (Table 2.1). The ‘Clip tool in ArcMap (ESRI 2013) and a GIS layer of all LMZs in NSW was used to create a further 16 sub-sets of database (*a*) for only the LMZ portion of each formation in NPWS land managed for biodiversity conservation.

2.2.3 Quantifying error in the database

In Chapter 3 I quantified the error in the fire history data in database (*a*) and the potential impact on biodiversity conservation. As a measure of error, I quantified the number of replicate records and the percentage of records missing attributes important for biodiversity conservation. This was done for NSW as a whole and each portion of each vegetation formation in NPWS Estate and non-NPWS in database (*a*). A Wilcoxon-signed rank test was used to compare the proportion of replicate records identified by the auto- and manual-cleans. The difference in the median percentage of records missing attributes in a given vegetation formation between NPWS Estate and non-NPWS was also tested, between eastern and western NSW, or between wet and dry vegetation. As there was only one wet formation in western NSW, wet and dry vegetation in eastern formations only were compared. As the NPWS_F dataset only contained records until 2016, the 2017 −2018 data fire records were omitted from all analyses using NPWS Estate data.

Table 2.2. Contents of each of the New South Wales fire history datasets

Contents of each of the four New South Wales fire-management datasets and number of records removed during pre-clean of datasets.

Dataset	NPWS_F	RFS_WF1	RFS_WF2	RFS_HR1
Responsible Agency	NSW NPWS	NSW RFS	NSW RFS	NSW RFS
Contents and years included	NPWS Estate Fire Records 1902-2016	NSW Wildfire Records 2001-2018	NSW Wildfire Records 1902-2007	RFS Hazard Reduction Records 18/10/2008-20/2/2016
Number of Records (before any cleaning)	31 845	10 648	32 158	94 300
Total area (ha)	27 469 242	8 886 119	19 963 284	1 583 621
No. deleted records (no fire year)	0	0	0	2 605
No. deleted records (not a fire)	0	0	0	82 443
No. deleted records ($<10m^2$)	167	39	1594	41
No. replicates found in ‘Spatial Join’	2 978	82	188	3
No. replicates found in ‘Find Identical’	510	781	1 738	221
Number of Records (after pre-clean)	28 190	9 746	28 638	9 086

* NSW NPWS: New South Wales National Parks and Wildlife Service
NPWS_F: NSW NPWS fire data set
NSW RFS: NSW Rural Fire Service
RFS_WF1: NSW RFS wildfire dataset 1 (2001 – 2018)
RFS_WF2: NSW RFS wildfire dataset 2 (1902 – 2007)
RFS_HR1: NSW RFS hazard reduction dataset (2008 – 2016)

Table 2.3. Attributes from the four New South Wales fire history datasets

For each attribute relevant to fire: name used by datasets; explanation of attributes; source dataset(s) (NSW Rural Fire Service (RFS_F1, RFS_F2, or RFS_HR) or NSW National Parks and Wildlife Service (NPWS_F)); and percentage of records missing each attribute after merging the four datasets and removing replicate records.

Attribute name	Explanation of attribute	Source dataset(s)	% of records missing attribute
Fire name[A]	Name given by fire agency	All	52
Year of fire[A]	Year fire occurred (expressed as a single year)	RFS_F1 / F2*	42
Fire size (area) [A]	Total number of hectares recorded as burnt	All	0
Fire perimeter length	Length (m) of perimeter boundary of fire polygon	All	0
Fire season / fire year[A]	Fire season, expressed over two calendar years (e.g., 1998-99)	RFS_F1, F2 / NPWS_F*	16
Fire start date[A]	Day/month/year the fire started	All	34[B]
Fire end date[A]	Day/month/year the fire extinguished	All	
Cause[A]	Fire cause, e.g., arson, lightning, campfire, equipment use, undetermined	All	79[C]
Fire type[A]	Wild or prescribed	NPWS_F*	0
Method class[A]	Hazard reduction method	RFS_HR*	0
Capture method	Method of mapping boundaries e.g., thermographic camera, satellite data, GPS airborne, GPS car, hand drawn	All	54
Capture source	Agency supplying data e.g., RFS, NPWS, Fire and Rescue, NSW Forestry Corporation	All	15
Intensity[A]	Measure of fuel consumption	NPWS_F*	82

* [A] used in analyses; [B] missing one or both start or end date; [C] including records with cause listed as ‘unknown’

* NSW NPWS: New South Wales National Parks and Wildlife Service; NPWS_F: NSW NPWS fire data set; NSW RFS: NSW Rural Fire Service; RFS_WF1 and WF2: NSW RFS wildfire datasets 1 and 2; RFS_HR1: NSW RFS hazard reduction dataset

2.2.4 Assessing completeness of the database

There is potential for error in interpretation of fire history due to missing records and it is important to understand the uncertainty associated with any dataset. To determine the completeness of the four electronic fire datasets, a search of the electronic newspaper archive of the National Library of Australia (Trove) was conducted. Trove is an online collection which allows full text searching of newspaper articles published in Australia from 1803 to 2009. The intention was not to compile a comprehensive fire history, and as such no other historic records were examined.

In Trove all available digital copies of 479 newspapers published in NSW between 1803 and 2009 were searched. The search term ‘bush fire’ was used to find potential articles. The criteria for inclusion of fires as relevant records were that they were within 10 km of vegetation that was extant in 2018 (including on private property).

The initial search encompassing the whole of NSW resulted in 450817 articles, so the first 100 articles per year were selected (or all articles if fewer than 100 per year) from 1800 to 2009. There were only 14 newspapers in the Trove archive after 1970, none of which had any reports of fires, so the results only include articles found between 1800 and 1969. No other sources of fire records were searched for after 1970 as satellite imagery and spatial mapping programs allowed more systematic data collection after that date.

Each article was skim-read to identify fires that met the criteria. Not all articles cited fire size, so a fire was included if it was described as large or was at least five hectares. Each fire identified from the Trove search was then cross checked to determine if it was recorded in database *(a)*.

A more systematic search was undertaken for each of the vegetation formations in the western part of NSW as there were fewer fires reported in the western half than the eastern half of the state. Reports of fires between 1800 and 1969 within all major towns that were settled and had newspapers in the 19th Century were searched for.

2.2.5 Assessing change in area burned

A common and important use for fire history data is to analyse change in the spatiotemporal patterns in fire activity. As fire patterns are predicted to further change with climate change in many ecosystems, the need for accurate and consistent methods for detecting change is required. One method for detect changes in scale, location, distribution, or timing is change point analysis (Fearnhead and Ragaill 2017).

Here I use change point analysis to test for temporal patterns in scale and location in recorded area burnt, missing attributes, or repeated records in database *(a)*. The original tests for change points were for detecting a single change point (Page 1955), more recently tests for multiple change points in time series data have been developed for use in areas such as finance and climate change, generally performed on large datasets. Use with small datasets may lead to excess noise, lack of statistical power (Andersen *et al.* 2009), and difficulty determining thresholds to compare the test statistic against (Ross *et al*. 2011), resulting in an increase in false positive detections. As database (*a*) is comparatively small (117 data points (years) from 1902 to 2018), consistency among seven methods of determining change points was compared.

Many of the most commonly used change point tests are parametric and their assumptions were not always met with database (*a*) data, but non-parametric tests also exist for single and multiple change point analyses. Two parametric methods (one single and one multiple) and five non-parametric methods for detecting change points (one single and four multiple) were used. All analyses were conducted in R (R Core Team 2018).

The two tests for a single change point were: (1) a non-parametric two-tailed hypothesis Pettitt test using the 'trend' Package (Pohlert 2018); and (2) an *F*-statistic using the 'strucchange' package (Zeileis *et al.* 2002).

The five tests for multiple change points were: (1) a parametric dynamic algorithm which estimates change points (with 95% confidence intervals) that minimise residual sum of squares (Bai and Perron 2003; Zeileis *et al.* 2003), (strucchange package (Zeileis *et al.* 2002)); (2) the 'E-Divisive' non-parametric method based on *U*-statistics (ecp Package (James and Matteson 2014)); and (3) a non-parametric Lepage-type hypothesis test based on Lepage (1971) (cpm Package (Ross *et al* 2011; Ross 2015)).

The Lepage and Mood tests appeared to detect a change point at 1937 for every formation. I was unable to determine when this was an error (possibly due to small sample size) or a real change point, so further tests designed to detect changes in location and scale parameters respectively were performed: (4) a non-parametric Mann-Whitney statistic (cpm Package (Ross *et al* 2011; Ross 2015)); and (5) a non-parametric Mood statistic (cpm Package (Ross *et al* 2011; Ross 2015)).

Data for total area burned per year were logarithm_{10} transformed to reduce skewness and heterogeneity of variance prior to change point analysis. Each dataset was converted to a time series and the seven change point tests performed.

2.3 Distributions of time since the most recent fire

In Chapter 4 I analyse the variation among, and predictors of distributions of time since the most recent fire among vegetation types. This was done for NSW as a whole and each portion of each vegetation formation in NPWS Estate and non-NPWS. I also compare distributions within areas managed for biodiversity conservation to the most diverse distributions achievable under management guidelines.

2.3.1 Calculating time since fire, fire frequency and fire intervals

The result of multiple overlapping fires through time in the landscape is small patches of the landscape with differing fire histories to the neighbouring patch. To determine the characteristics of the fire history for all extant vegetation in NSW (time since fire, fire frequency and fire intervals) it was necessary to create a new fire database. This was done using the 'Count Overlapping Polygons' (Honeycutt 2012) tool in ArcMap (ESRI 2013), which defines the boundaries of each area which had a differing fire history to its neighbouring areas. The final step of the tool uses the 'Spatial Join' tool to count the number of polygons that overlap the centroid. The output contains a 'Join Count' field which lists the number of polygons that overlapped each centroid.

A unique identifying number was assigned to each new polygon in the output. This was then joined back to the original database shapefile using the 'Identity' tool, which matched the output polygons with the database polygons based on their spatial locations. The resulting attributes table contained all the original attribute information from the database and the new join count and unique identifying number for each polygon. Polygons with matching unique identifying numbers were the overlapping polygons that were identified from the 'Count Overlapping Polygons' tool and each was from a different fire. The fire history for each polygon was determined and each subsequent year was appended to the most recent record (e.g., F1, F2…). The interval between each fire was also calculated and appended to the most recent record (e.g., INT1, INT2…). The 'Delete Identical' tool was used in ArcMap to remove all remaining records with matching unique identifying numbers.

This resulted in a new dataset of 451 684 polygons within extant vegetation with unique fire histories (hereafter database (*b*)), ranging in size from 0.000007 m^2 to 156 795 6 ha. The 110 515 records (109 ha) that were Polygons <50 m^2 were removed as they were most likely an artefact of boundary recording errors, as most occurred along the road edges and shorelines. For each of the remaining 341 169 polygons the number of years between June 2018 and the most recent fire in that polygon was determined. GIS layers of the vegetation formations of NSW (version 3.03, Keith and Simpson 2010) were used to create 16 separate subsets of database (*b*), one for each vegetation formation in NSW. The ‘Clip tool in ArcMap (ESRI 2013) and a GIS LMZ layer was used to create a further 16 subsets of database (*b*) for only the LMZ portion of each formation in NPWS LMZ. A further 16 subsets of database (*b*) were then created for the proportion of each vegetation formation not within NPWS Estate LMZ (hereafter non-NPWS).

2.3.2 Calculating time since fire distributions

Time since the most recent fire (TSMRF) distributions were created by calculating the proportion of extant vegetation with the most recent fire in each year of the 92-year fire history using database (*b*). These distributions were used to compare the synchronicity of the timing of fire events among vegetation types. The cumulative proportion with the most recent fire in, or prior to each year was then calculated (C_TSMRF). These distributions were used to determine the skew towards longer or shorter fire intervals among vegetation types. Both distributions were created for each vegetation type in NSW, and for the NPWS_LMZ portion and the non-NWPS portion of each vegetation type. The same distributions were then calculated for the 82-year fire history to 2008, and 72-year fire history to 1998.

2.3.3 Distributions in areas managed for biodiversity conservation

The cumulative proportion distributions of the greatest diversity of time since fire spread over 92 years and within the recommended thresholds for each formation (Kenny *et al.*

2003; Office of Environment and Heritage 2013) were calculated for each of the 12 formations with recommended intervals. For example, a formation with recommended thresholds of minimum 5 years and maximum 50 years would result in 35/5 = 7% of the formation at each of 1 to 5 years since fire; 50/45 = 1.1% at each of 6 to 50 years since fire; and 35/42 = 0.8% at each of 51 to 92 years since fire. For each vegetation formation with a fire management guideline, the percentage of the formation with the most recent fire within the guideline thresholds, the percentage below the minimum guideline, and the percentage above the maximum interval was calculated for the NPWS_LMZ portion and the non-NPWS portion.

Using a one-way Analysis of Similarity (ANOSIM) the C_TSMRF distributions and synchronicity of timing of the most recent fire events were compared among vegetation types in NSW, within NPWS LMZs, and for non-NPWS. ANOSIM was also used to compare distributions with the most diverse range of time since fire distribution achievable, based on fire management guidelines (Kenny *et al.* 2003; Office of Environment and Heritage 2013). Data were square-root transformed prior to calculating Bray-Curtis similarity matrices. Hierarchical cluster analyses were used to determine the similarity of distributions among formations (regional scale) and among classes (local scale). To quantify the amount of variation among class distributions within a formation, Bray-Curtis similarities of distributions across all classes within each formation were compared. These analyses were conducted using PRIMER v7 (Clarke *et al.* 2014).

The C_TSMRF distributions of the NPWS LMZ portion of each vegetation type was then compared to the non-NPWS portion distribution using a Kolmogorov-Smirnov test (ks.test; R Core Team, 2020). Further details of all data analyses are provided in Chapter 4.

2.3.4 Predictors of distributions of time since the most recent fire

In chapter 4, I examined the relative importance of climate, location, population density, land use, and fire history as predictors of the distributions of time since fire. I used the Interim Biogeographic Regionalisation for Australia (IBRA) bioregion boundaries as location predictors. These are delineated based on common environmental, vegetation and land use influences (Thackway and Cresswell 1995). Vegetation formations and classes are not restricted to one bioregion and may span many.

For the six most eastern IBRA bioregions in NSW: New England Tablelands (NET), NSW North Coast (NNC), South East Corner (SEC), South East Highlands (SEH), South East Queensland (SEQ), and Sydney Basin (SYB) (Figure 2.2; Table 2.4, A2.2), the proportion of each vegetation class, and the proportion within the LMZ portion of each class within each bioregion was calculated. Western bioregions were not used as there was insufficient fire data to analyse. Classes with <1000 ha within a bioregion (and <500 ha within the LMZ portion of each bioregion) were deemed to have insufficient fire history data and were excluded form the BEST analyses.

The distribution of time since fire for each portion of each class within each bioregion was calculated. Predictors included two climatic variables, six land use variables, a population density variable, fire history variables, and distance to roads/fire trails (Table 2.4) and were calculated for each portion of each class within each bioregion (and separately for the LMZ portion of each class). Predictors for temperature, precipitation, and human population density were calculated using the zonal statistics tool in ArcMap (ESRI 2013). The six land use predictors provided a measure of proximity to ignition sources and were calculated as the percentage of each vegetation type within each land use category (Table 2.4). The distance to roads/fire trails also provided a measure of proximity to ignition sources and was calculated from a grid point every 200 m and averaged. The percentage of each vegetation type with two, three, or four previous fires recorded were used as predictors of the relative importance of fire history in determining the distributions of time since fire. I limited these variables to four fires, as there was not enough fire history data to calculate more.

BEST analysis (PRIMER v7; Clarke *et al.* 2014) was used to examine the relative importance of the 13 variables as predictors of the distribution of time since fire (Table 2.4). BEST analysis was used to find the best match between Bray-Curtis similarity matrices of time since fire and Euclidian distance matrices of environmental variables (Clarke and Ainsworth 1993).

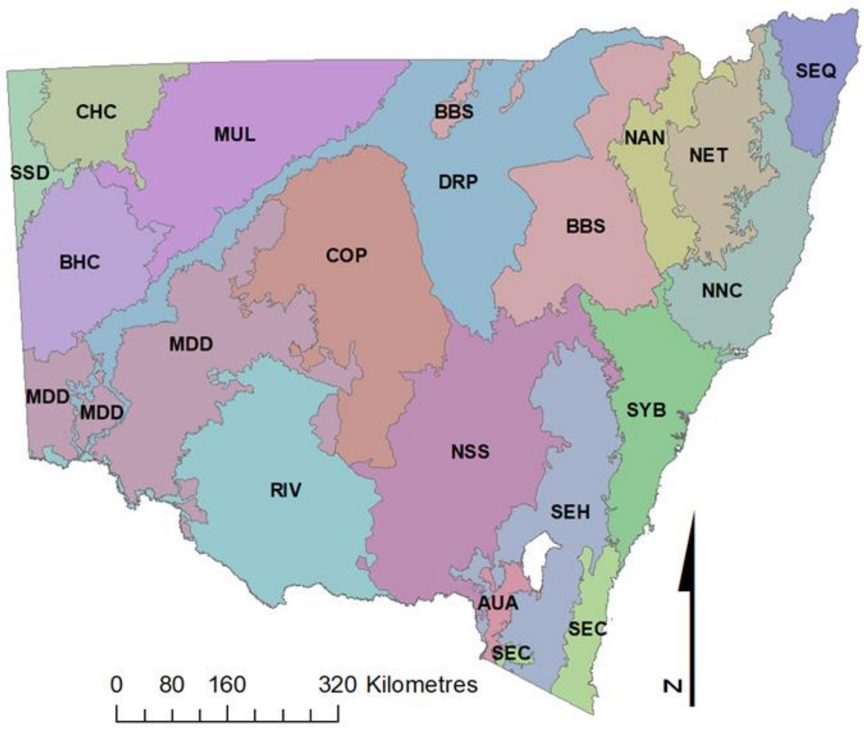


Figure 2.2 Interim Biogeographic Regionalisation for Australia (IBRA) regions of New South Wales (see Table A2.2 for full name and further details)

2.4 Assessing fauna habitat – pilot study

I used database (*a*) and the GIS layers of the vegetation formations of NSW (version 3.03, Keith and Simpson 2010) to select sites with the appropriate fire history for Part 2 of my study. Whilst Part 1 of my study was based on the fire history for the whole of NSW, Part 2 required vegetation formations with sufficient fire history to ensure adequate replication of treatments. As Part 2 of my study was an examination of the relative influence of time-since-fire, inter-fire interval, environmental and abiotic factors, and vegetation type on fauna habitat at a fine scale, the field sites also required vegetation formations with classes that spanned a large geographical area, but that also converged in a central location. These requirements, as well as time factors, limited the number of formations I was able to sample in.

A pilot study was undertaken to determine the level of sampling required to give sufficient power to analyses to detect differences in habitat within different vegetation types and with different fire histories, however, still be manageable in the timeframe of my study.

2.4.1 Field work – pilot study

The Warrumbungle National Park in north-western New South Wales (Figure 2.3) was selected for the pilot study as there are good fire history records for the park for at least the past 30 years, and one of the dominant vegetation formations is the Dry Sclerophyll Forests (Shrubby/Grassy) sub-formation, which spans the entirety of the park.

From January to November in 2017 sampling was undertaken in the Warrumbungle National Park. Four sites with a similar time since fire but different intervals to the previous fire were selected within vegetation mapped as North-west Slopes Dry

Sclerophyll Woodlands, a vegetation class within the Dry Sclerophyll Forests (Grassy/Shrubby) sub-formation (Keith 2004; Figure 2.3; Table 2.5). The most recent fire for three of the sites was in 2013, and the intervals between the most recent fire and the fire before were 16, 23 and 39 years. The fourth site did not burn in the 2013 fire and had no fire recorded in database (*a*). It is likely that the fourth site had not burnt for >30 years as there are good records for the park from 1990 onwards (Table 2.5).

2.4.2 Site layout and sampling protocol – pilot study

At each site, any evidence of human disturbance (including felled or ringbarked trees, cut stumps, or tracks) within 100 m^2 were recorded. The diameter at breast height (DBH) and height of the most fire sensitive tree species in the site was recorded, as an estimate of time since the last fire. Within each site, two parallel 100 m × 10 m transects were laid out, both at least >50 m from the nearest road or trail. The two transects were positioned at a distance of 30 m apart. Along each transect ten 10 × 10 m quadrats were measured out and numbered from one to ten (Figure 2.4). Within quadrats 1, 4, 7 and 10, a 2.5 m × 2.5 m sub-plot was placed in each corner (Figure 2.5). Photos were taken from each corner of the ten quadrats looking toward the centre of the quadrat. Data for habitat attributes in trees and logs were collected from quadrats 1 – 10, and data for habitat attributes relating to ground cover, strata heights, vegetation density and coarse woody debris were collected from quadrats 1, 4, 7, and 10.

Table 2.4. Variables used as predictors of distributions of time since fire

Predictor variable category, variables within each category and source of data used.

Predictor category	Predictor variable	Source
Climate	Mean annual precipitation	Harwood 2019
	Mean annual temperature	Harwood 2019
Location	% of vegetation types within six eastern IBRA* bioregions in NSW	Dept. of Agriculture, Water and the Environment 2020
Population	Mean number of people per square kilometre	Australian Bureau of Statistics 2018
Land use	% of vegetation type within: grazing native vegetation; non-wooded agriculture; parks/reserves and conservation areas; riparian and water bodies; urban/human habitation; wooded agriculture	Dept. of Planning, Industry and Environment 2018
Fire history	% of vegetation type with: two; three; or four or more recorded fires	NSW RFS and NSW NPWS fire history datasets
Distance to nearest road/fire trail	Mean distance (km) per 200 m to the nearest road/fire trail per square kilometre	NSW Government Spatial Services 2021

*IBRA: Interim Biogeographic Regionalisation for Australia

Table 2.5. Fire history for pilot study sites in the Warrumbungle National Park

For each site in the pilot study, site name, year of most recent fire, previous fire history, and date the site was sampled

Site	Fire 1	Fire 2	Fire 3	Date sampled
WNP01	2013	1997	1967	10-12/01/2017
WNP02	2013	1990	1970	26-27/09/2017
WNP03	2013	1974		28/09/2017, 07/11/2017
WNP04	No fires recorded			8-9/11/2017

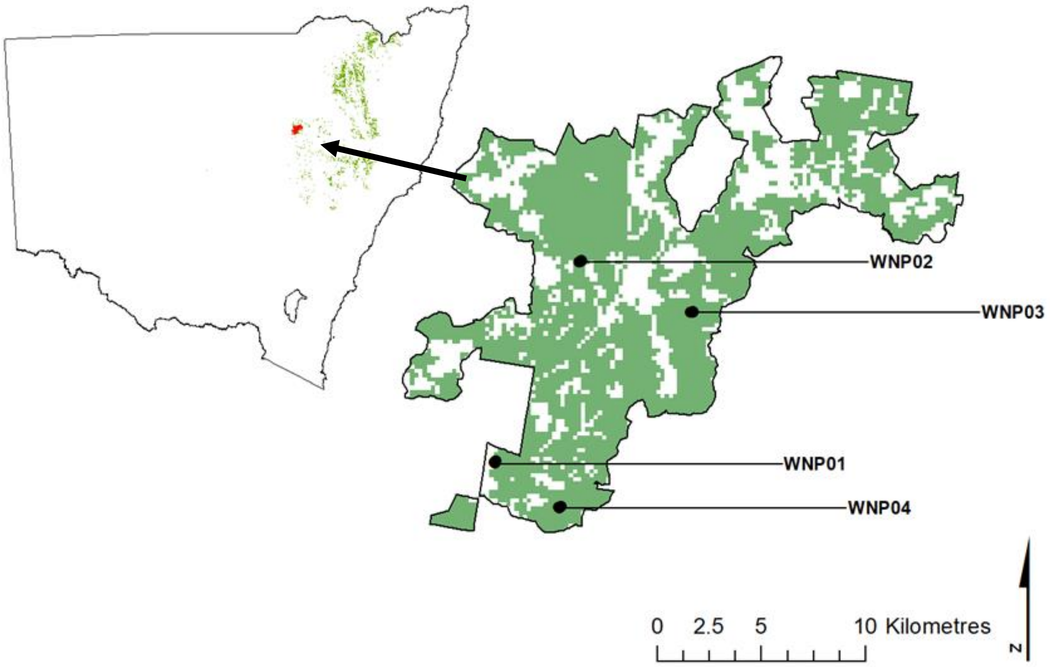


Figure 2.3 Location of the Warrumbungle National Park (red) and extent of the North-west Slopes Dry Sclerophyll Woodlands vegetation class within New South Wales (green). Inset: location of the four pilot study sites and extent of the North-west Slopes Dry Sclerophyll Woodlands vegetation class (green) within the Warrumbungle National Park

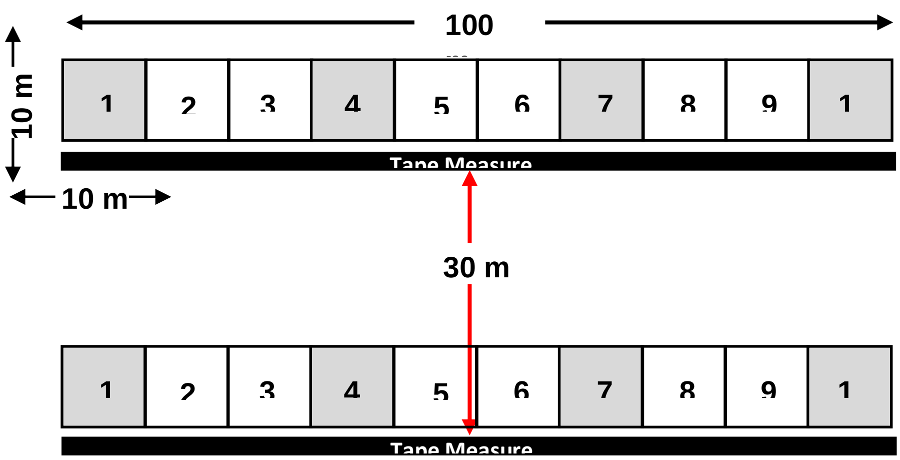


Figure 2.4 Layout of each transect within each site of the pilot study, showing quadrats one to ten. Extensive sampling was undertaken in quadrats 1, 4, 7, and 10 (grey).

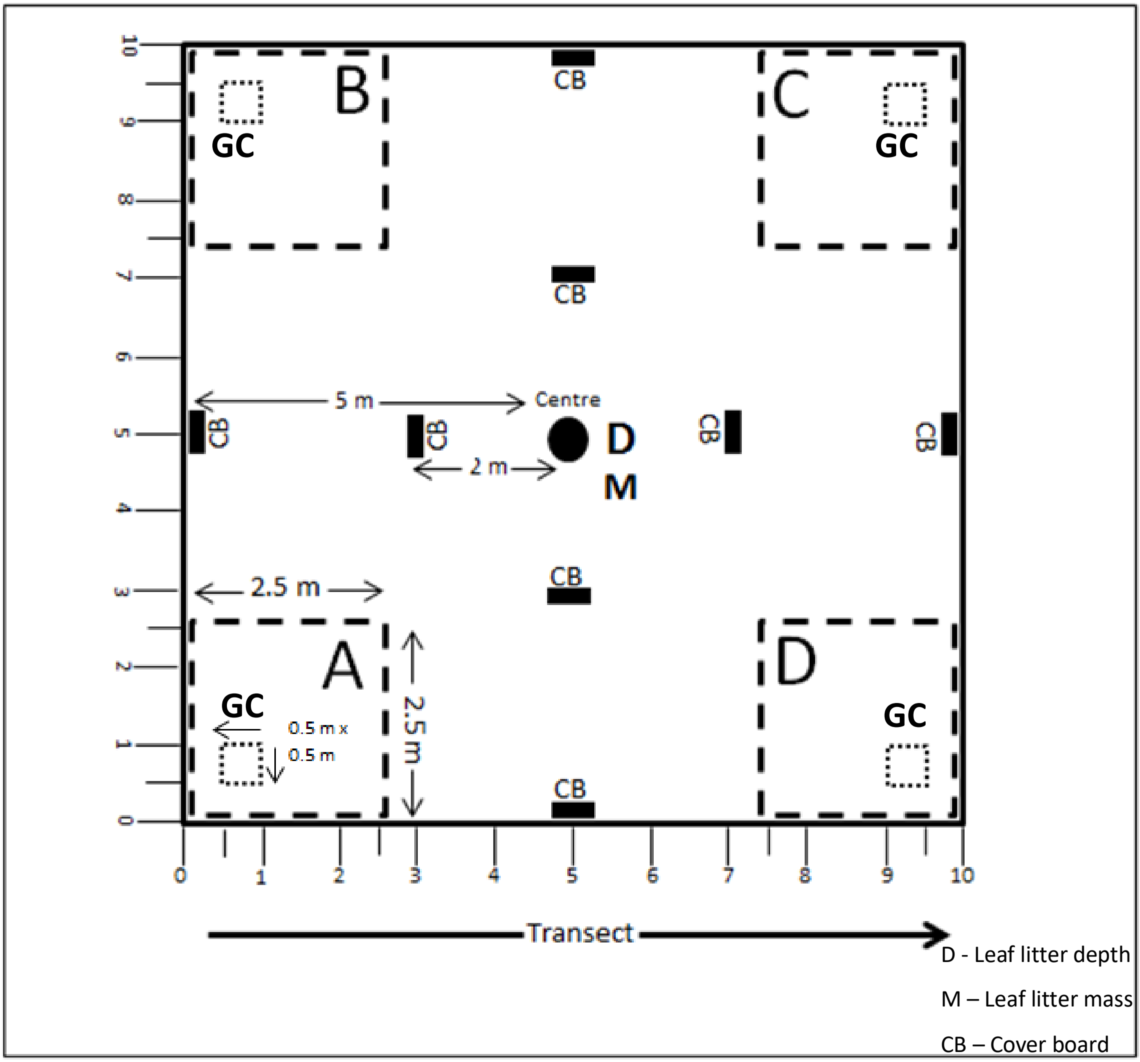


Figure 2.5 Layout of 10 m ×10 m quadrats 1, 4, 7, and 10 showing location of the four sub-plots (A – D), location of ground cover measurements (GC), distance and location to the centre of the quadrat for coverboard measurements (CB), and location of leaf litter depth (D) and litter mass (M) measurements. The total area of rocks was measured in the sub-plots A – D.

2.4.3 Habitat attributes

2.4.3.1 Solar radiation transmittance and canopy structure

Hemispherical photographs were taken at the centre of quadrats 1, 4, 7, and 10 (Figure 2.5) using a Canon (DS 126061) camera fitted with a Sigma 4.5 mm fisheye lens. The camera was aimed vertically at a distance of ~1.3 m above the ground with the top of the image aligned to magnetic north.

A tree was defined as a plant with a stem diameter at breast height (DBH at 1.3 m above ground) of ≥15 cm and a height of > 2 m. For each tree, the species (at a minimum genus), number of stems and condition of each stem (live or dead) were recorded. The DBH over bark, height, and height above ground of the lowest live foliage was measured. For trees with multiple stems, a DBH was recorded for all stems if the combined cross-sectional area of all stems was greater than 177 cm^2 (the cross-sectional area of a stem 15 cm diameter). The presence and height of any scorching on each stem was also recorded. For stems that had lost their bark and the presence of scorching was unable to be determined, the scorch height was recorded as unknown.

For each stem I recorded the condition (live or dead) of any epicormic growth and basal resprouts and height above ground of the lowest epicormic growth. The number, condition, and height of the tallest basal resprout were measured. The presence of any decorticating bark (stringy ribbons of bark, or thick bark with visible fissures) and mistletoe was noted.

For each stem I used binoculars to count, from the ground, the number of hollows. A hollow was defined as a cavity with an entrance diameter of >2 cm and where the depth of the cavity was greater than the smallest entrance diameter. For each hollow the orientation of the entrance and the hollow type were recorded (Figure 2.6). Where the hollow could be reached, the length of each dimension was measured, otherwise estimated.

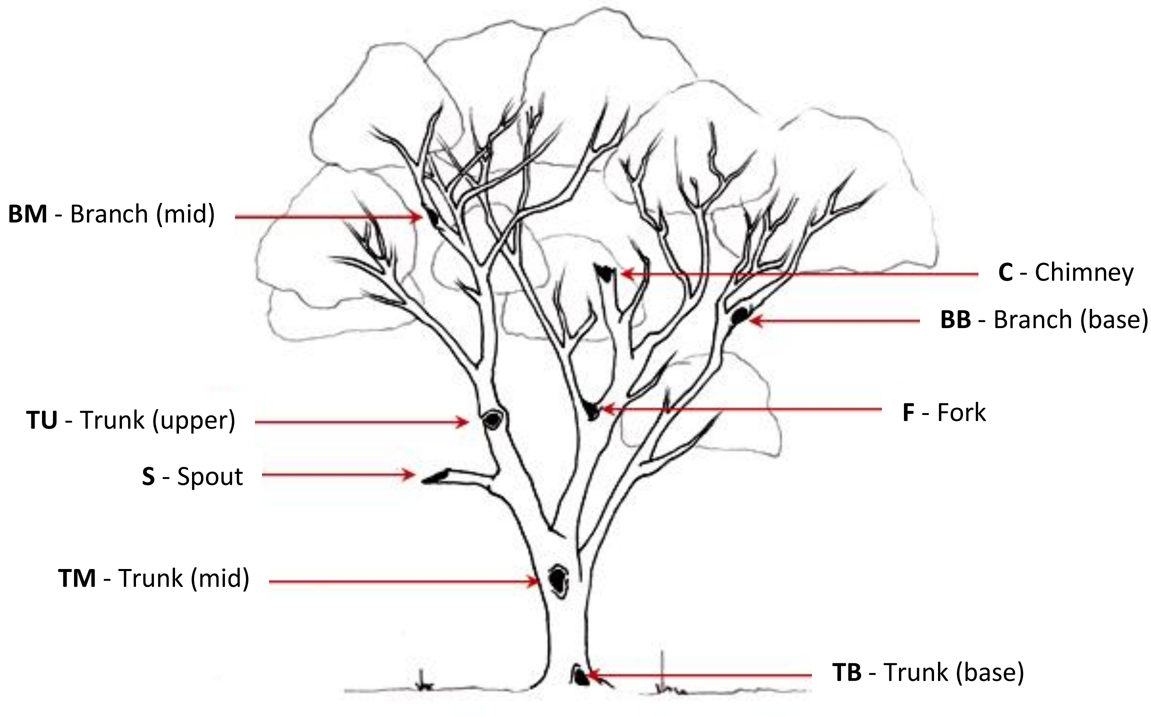


Figure 2.6 Hollow type, name, abbreviation, and location in tree (Figure: Rayner 2008)

2.4.3.2 Understorey vegetation structure

Visual estimates of the vegetation density were measured using a 20 cm × 50cm chequered cover board, with 10 alternating 10 cm × 10 cm black and white squares (Figure 2.7) at four heights (0 – 20 cm, 20 – 50 cm, 50 – 100 cm and 100 – 150 cm) above the ground. Estimates of the percent of the board covered by vegetation was recorded at the mid-point of all four sides of quadrats 1, 4, 7, and 10 (Figure 2.5). The cover board was in the centre of the quadrat, facing the observer in all directions and measurements were taken at an observer-to-coverboard distance of 2 m and 5 m in each direction.

Within each sub-plot in quadrats 1, 4, 7, and 10 (Figure 2.5) heights of the vertical mid-canopy vegetation were measured. The lowest and highest live foliage of the tallest plant with a DBH <15 cm in three strata groups (near surface: live foliage 0 cm – 49 cm; elevated: live foliage 50 cm – 99 cm; intermediate: live foliage 1 m – 2 m) were taken. The lowest measurement for grass species was the ground, for non-grass species the lowest measurement was the lowest foliage from a stem (Figure 2.8). Evidence of any scorching/fire scars on each plant measured was noted.

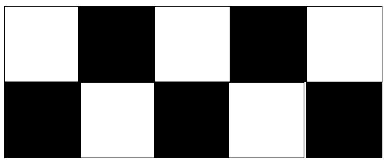


Figure 2.7 Cover board comprised of 10 alternating 10 cm × 10 cm black and white squares used to estimate horizontal vegetation density

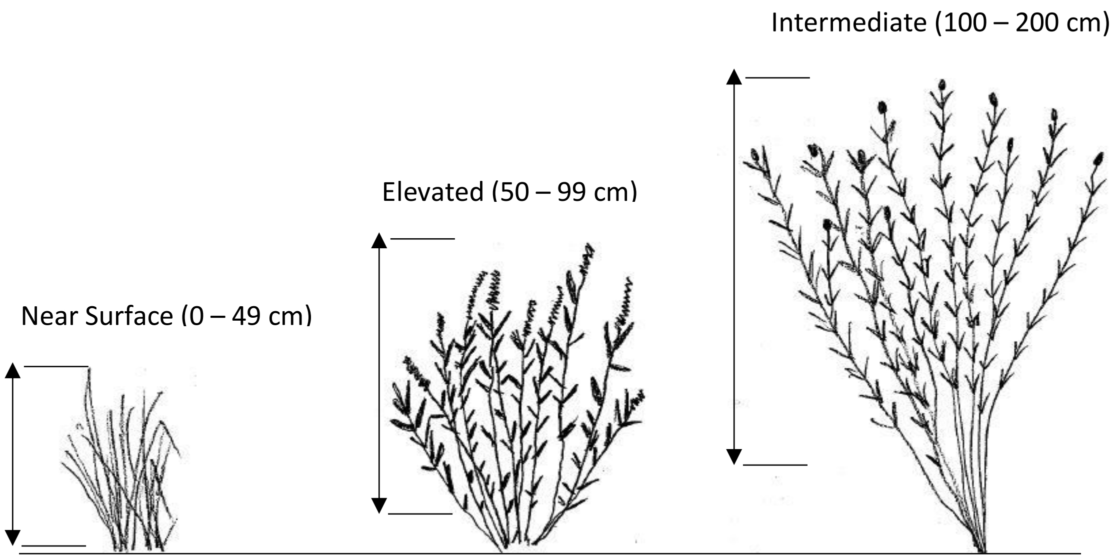


Figure 2.8 Near surface, elevated and intermediate layers used to measure height of the mid-canopy vegetation (figure not to scale). Measurements for each layer were taken from the lowest live foliage on a stem (from the ground if grass)

2.4.3.3 Logs and coarse woody debris

Logs were defined as a fallen branch or tree trunk with a diameter ≥10 cm. The total length, and length of any scorching on all logs with ≥50% of its length within each quadrat was measured. Branches (diameter ≥10 cm) from the main leader were recorded as separate logs. The diameter was recorded at each end and in the middle of each log. The height above ground was measured from the lowest point (0 cm if the log was touching the ground) to the highest point to give an indication of the vertical arrangement of the habitat within the quadrat. The length of any part of the log that was above the ground (from the point the log left the ground) was recorded. If multiple sections of the log were above the ground, then separate measurements were taken for each section. Logs that were split or disintegrated were measured if the average of the vertical and horizontal diameter was >10 cm.

A hollow was defined as any cavity in the log where the length was greater than the internal diameter. Measurements of the length and diameter of any hollows were recorded for each log.

A stump was defined as any trunk with a diameter >10 cm and a height >30 cm and <1.3 m. The diameter at 30 cm, height and scorch height of any stumps were recorded. If the stump was hollow (i.e., the internal hollow length was greater than its diameter), the length and diameter of the hollow was recorded.

Coarse woody debris (CWD) was defined as any sticks, branches, or logs with a diameter >2 cm and < 10 cm. The length of each piece of CWD in each sub-plot in quadrats 1, 4, 7, and 10 was measured (Figure 2.5). If any CWD extended beyond the sub-plot only the section that was inside was measured. The diameter (cm) was measured at each end and in the centre of the CWD and averaged. The height above ground (cm) was also measured at the lowest (0 cm if it was touching the ground) and highest points. The arrangement was grouped into two categories, clumped (if the CWD was touching 3 or more other pieces of CWD) or dispersed (if the CWD was touching 2 or less pieces).

2.4.3.4 Ground cover attributes

Leaf litter depth was measured at the centre of quadrats 1, 4, 7, and 10 (Figure 2.5) by placing a ruler orthogonal to the ground and measuring the highest point of any leaf litter surrounding the ruler.

Leaf litter was collected from the centre of quadrats 1, 4, 7, and 10 (Figure 2.5). All leaf litter from an area of 50 cm × 10 cm was collected down to soil level, placed in a bag, and weighed using a spring balance to the nearest 1 gram. The leaf litter was dried in an oven at 80^{o} C to constant weight (i.e., until there was a change of <0.15g for two consecutive days) for at least five days, with the weight recorded at approximately the same time each day. As the weight of each bag only decreased by <0.15 g after 72 hours, it was determined that future leaf litter samples would be dried for 72 hours.

The relative cover at ground level of eight ground cover features (living plants, leaf litter (including sticks <2 cm diameter), bare ground, fine woody debris (sticks >2 cm and <5 cm diameter), CWD, logs, rocks and soil crusts) was measured in the corner of each sub-plot (A, B, C, and D, Figure 2.5) in quadrats 1, 4, 7, and 10. Data were collected using a 0.5 m x 0.5 m quadrat with string in each direction, creating twenty-five 5 cm × 5 cm squares (Figure 2.9). A tally of the occurrence of the eight ground cover features was taken for the 16 points the strings intersected. If more than one ground cover feature occurred at a point the topmost feature was recorded.

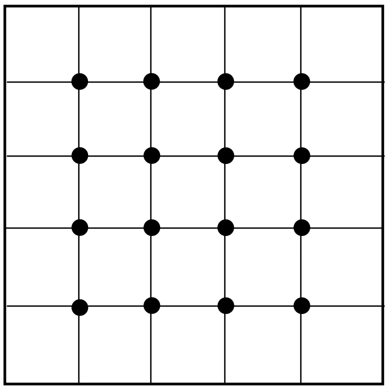


Figure 2.9 Ground cover quadrat measuring 0.5 m × 0.5 m with string in each direction. ● indicates sample point where the strings intersected

2.4.3.5 Rocks

Rocks were defined as any medium or large rocks where the shortest length was >5 cm. The total area (m^2) of all rocks within each sub-plot in quadrats 1, 4, 7, and 10 was measured (Figure 2.5).

2.4.4 Data analysis – pilot study

Analysis of the pilot data was undertaken to determine if sufficient sampling power could be gained from a less intensive sampling regime. Ten alternative configurations of the sampling protocol were chosen, with the number of quadrats sampled ranging from four to ten, and the number of sub-plots sampled ranging from 8 to 16, with differing arrangements of transects, quadrats, and sub-plots sampled (Table 2.6).

For each attribute sampled in the pilot study, the mean, standard deviation and 95% confidence intervals per sample unit was calculated and used to compare the ten alternative protocols to the raw data (Figures A1.1 – A1.12). The sampling protocol that was most consistently similar to and within the 95% confidence interval of the raw data was Option four (Figure 2.6). In Option four, trees, logs, canopy structure and solar radiance transmission were measured in quadrats 1, 4, 7 and 10 in both transects and the remaining habitat attributes in sub-plots A and B in quadrats 1, 4, 7 and 10 for both transects (Figure 2.10, 2.11, A1.1 – A1.12). Option four was then used as the sampling protocol for data collection for the remaining field work.

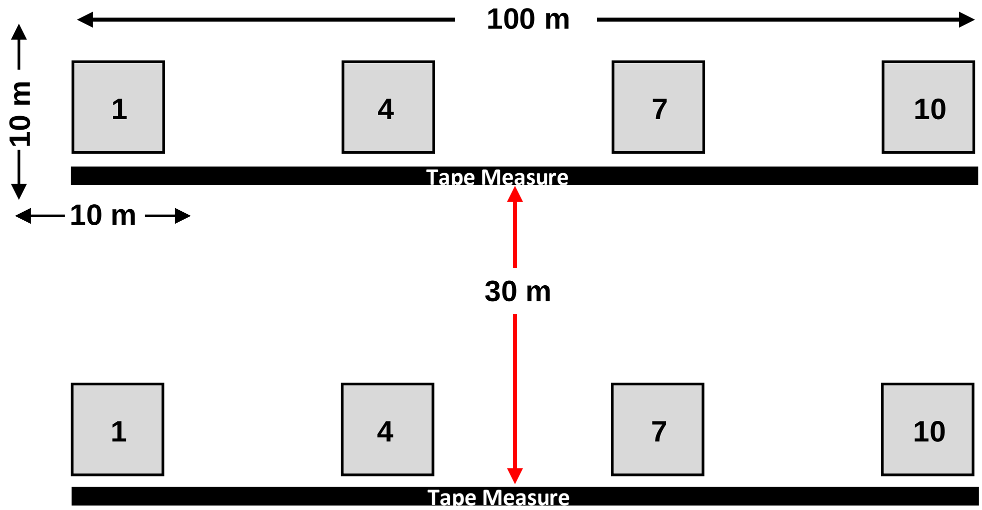


Figure 2.10 Layout of each transect within each site of the study. The final sampling protocol consisted of sampling in quadrats 1, 4, 7, and 10 (grey).

Table 2.6. Alternative sampling protocols

For the ten alternative sampling protocols tested, the number of transects, quadrats and sub-plots sampled, and the configuration of quadrats and sub-plots

Option	Transects sampled	No. quadrats sampled	No. sub-plots sampled	Quadrats sampled	Sub-plots sampled
Full sampling Protocol					
	T1, T2	20	32	All	All
Alternative sampling protocols					
1	T1	10	16	T1 all	T1 all
2	T2	10	16	T2 all	T2 all
3	T1, T2	8	8	1, 4, 7, 10	A
4	T1, T2	8	16	1, 4, 7, 10	A, B
5	T1	4	8	1, 4, 7, 10	A, B
6	T2	4	8	1, 4, 7, 10	A, B
7	T1, T2	4	16	1.1, 1.7, 2.4, 2.10	A, B, C, D
8	T1, T2	4	16	1.4, 1.10, 2.1, 2.7	A, B, C, D
9	T1, T2	4	16	1.1, 1.4, 2.7, 2.10	A, B, C, D
10	T1, T2	4	16	1.7, 1.10, 2.1, 2.4	A, B, C, D

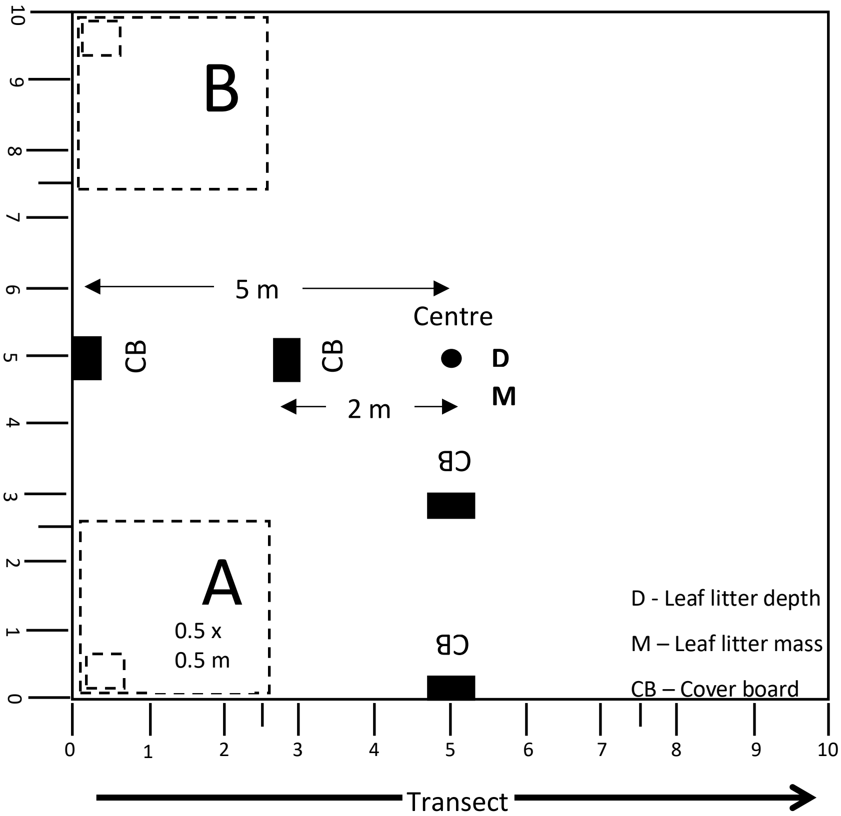


Figure 2.11 Layout of final sampling protocol of 10 m ×10 m quadrats 1, 4, 7, and 10 showing location of the two sub-plots (A and B), location of ground cover measurements (GC), distance and location to the centre of the quadrat for coverboard measurements (CB), and location of leaf litter depth (D) and litter mass (M) measurements. The area of rocks was measured in the sub-plots A and B

2.5 Field work

Field work was conducted within the Dry Sclerophyll Forests (Shrubby sub-formation) (DSFS; Keith 2004) vegetation in New South Wales (NSW). This sub-formation was chosen as there was sufficient fire history to ensure adequate replication of treatments and also it contained classes that spanned a large geographical area, but that also converged in a central location (Figure 2.12). DSFS covers 4.87 million hectares (ha) of eastern NSW and extends ~850 km from north to south and ~450 km east to west, commencing on the western side of the Great Dividing Range and extending east to the coast. DSFS is classified by structural and physiognomic features (Keith 2004) and is characterised by a canopy of low scleromorphic trees, typically eucalypts, a scleromorphic shrub layer, and a sparse ground layer (Keith 2011). DSFS occurs on low nutrient soils where mean annual rainfall ranges from 600 – 1000 mm but increases to 1000 – 1500 mm along the coastal edge (Bureau of Meteorology 2020*a*).

DSFS is further classified in to 14 vegetation classes, defined by floristic similarities, and which share a common structural form (Keith 2004; Table 2.7). Sites were selected within three classes (Western Slopes Dry Sclerophyll Forests (DFS), Sydney Hinterlands DSF and Southern Tablelands DSF) that together, spanned the length of NSW (Figure 2.12; Table 2.7). The three classes converge at the north-western edge of the Sydney basin (Figure 2.12).

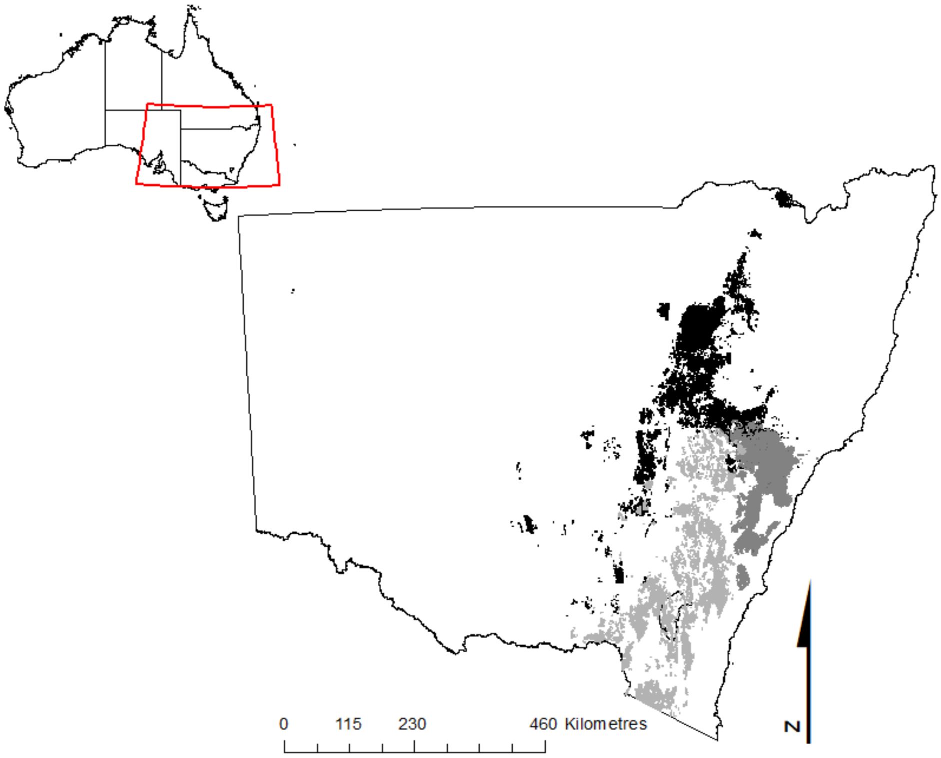


Figure 2.12 Location and extent of the Western Slopes Dry Sclerophyll Forests (DSF; black), Sydney Hinterland DSF (dark grey), and Southern Tablelands DSF (light grey) vegetation classes within the Dry Sclerophyll Forests (Shrubby sub-formation) in New South Wales

Table 2.7. Vegetation classes

Vegetation, location and habitat descriptors for the Western Slopes, Sydney Hinterlands and Southern Tablelands Dry Sclerophyll Forests vegetation classes (Keith 2004)

Vegetation Class	Western Slopes Dry Sclerophyll Forests	Sydney Hinterland Dry Sclerophyll Forests	Southern Tablelands Dry Sclerophyll Forests
Vegetation description	Open eucalypt forest or woodland	Open eucalypt forest or woodland	Open dry eucalypt forest or woodland
Dominant canopy species	*Eucalyptus dealbata* *E. sideroxylon* *Callitris endlicheri* *C. glaucophylla*	*Angophora bakeri* *Corymbia eximia* *C. gummifera* *Eucalyptus beyeriana* *E. punctata* *E. sclerophylla* *E. sparsifolia*	*Eucalyptus cinerea* *E. dalrympleana* *E. dives* *E. macrorhyncha* *E. rossii*
Canopy height	10-25 m	10-25 m (stunted on ridges and dry slopes)	15-20 m
Understorey layer	Dominated by sclerophyllous shrubs	Prominent sclerophyll shrubs	Open to sparse, comprised of sclerophyll shrubs
Ground layer	Dominated by forbs, few grass species	Open groundcover of sclerophyll sedges, including ferns and speargrass	Open groundcover of scramblers, forbs and tussock grasses
Found	Western edge of Great Dividing Range on slopes and low ridges on granite outcrops and sandstone peneplains	Largely restricted to the Sydney Basin, on slopes, gullies and sandstone ridges	Straddles the Great Dividing Range in southern NSW on exposed slopes and ridges
Elevation	<600 m ASL	<600 m ASL	600 – 1100 m ASL
Soils	Low-fertility sandy loams	Infertile soils	Infertile soils
Mean annual rainfall	< 500 mm	650 – 950 mm	600 – 1500 mm

*ASL: Above sea level

2.5.1 Site selection

Fire history data was used to select fifty-four sites, six replicates in each vegetation class (Table 2.8; Figure 2.13). Sites were selected to span most of the extent of each class (Figure 2.13). All sites were within Land Management Zones (LMZ) in National Parks, Nature Reserves, State Conservation Areas or Regional Parks (Figure 2.13). Sites were selected to have the most recent fire between three and nine years since 2018 (most burned in 2013; Table 2.8). Fifty-one of the sites had more than one fire recorded in the fire database and three sites only had one fire recorded (Table 2.8). Sites were grouped based on inter-fire intervals (the time between the most recent fire and the fire before): between 0 and 6 years (less than the minimum recommended fire interval for Dry Sclerophyll Forests (Shrubby sub-formation); Kenny *et al.* 2003; Figure 2.14); between 7 and 29 years (within the recommended fire intervals; Figure 2.15); and ≥30 years (longer than the maximum recommended fire interval; Figure 2.16). Sites were selected to cover the greatest range of inter-fire intervals within the guidelines as possible. Within each fire interval and vegetation class combination, there were six replicates (Figures 2.14 – 2.16). The minimum distance between sites within a fire interval category for the same vegetation class was 10 km, with the majority separated by >60 km, and up to 450 km (Figures 2.14 – 2.16). The minimum distance between sites within a fire interval but in different vegetation classes was 400 m (Figures 2.14 – 2.16).

Table 2.8. List of study sites

For each site: vegetation class, name of National Parks and Wildlife Service (NPWS) Estate, years between sampling and the most recent fire (TSF), recommended interval range in years (Range), year of most recent fire (Fire 1), year of previous recorded fire (Fire 2), number of years between Fire 1 and Fire 2 (Interval), and the date sampling occurred (Date). For Fire 1, W = wildfire and all other fires were prescribed

Site	Vegetation Class	NPWS Estate	TSF	Range	Fire 1	Fire 2	Interval	Date
JW001	Western Slopes	Durridgere State Conservation Area	6	0-6	2013	2010	3	11/09/2019
JW002	Western Slopes	Goulburn River National Park	6	0-6	2013	2011	2	02/07/2019
JW003	Western Slopes	Goobang National Park	6	0-6	2013	2008	5	06/08/2019
JW004	Western Slopes	Goonoo State Conservation Area	6	0-6	2013	2011	2	08/08/2019
JW005	Western Slopes	Timallallie National Park	6	0-6	2013 (W)	2007	6	16/08/2019
JW006	Western Slopes	Pilliga East State Conservation Area	9	0-6	2010	2009	1	19/08/2019
JW007	Western Slopes	Wollemi National Park	6	7 -29	2013	1985	28	22/07/2019
JW008	Western Slopes	Timallallie National Park	6	7 -29	2013 (W)	2009	9	18/08/2019
JW009	Western Slopes	Binnaway Nature Reserve	6	7 -29	2013	2002	11	14/08/2019
JW010	Western Slopes	Pilliga East State Conservation Area	6	7 -29	2013	1997	16	20/08/2019
JW011	Western Slopes	Goobang National Park	9	7 -29	2010	1983	28	07/08/2019
JW012	Western Slopes	Nangar National Park	8	7 -29	2011	1998	12	16/09/2019
JW013	Western Slopes	Wollemi National Park	6	30+	2013	1982	31	13/09/2019
JW014	Western Slopes	Goobang National Park	8	30+	2011	1979	32	08/08/2019
JW015	Western Slopes	Warrumbungle National Park	6	30+	2013 (W)	1935	78	15/08/2019
JW016	Western Slopes	Pilliga East State Conservation Area	6	30+	2013	1951	62	21/08/2019
JW017	Western Slopes	Bullala National Park	7	30+	2012			22/08/2019

Site	Vegetation Class	NPWS Estate	TSF	Range	Fire 1	Fire 2	Interval	Date
JW018	Western Slopes	Weetalibah Nature Reserve	5	30+	2015	1965	50	13/08/2019
JW019	Sydney Hinterland	Ku-ring-gai Chase National Park	11	0-6	2009	2003	6	07/01/2020
JW020	Sydney Hinterland	Goulburn River National Park	6	0-6	2013	2011	2	01/07/2019
JW021	Sydney Hinterland	Berowra Valley National Park	8	0-6	2012	2011	1	09/01/2020
JW022	Sydney Hinterland	Blue Mountains National Park	7	0-6	2013 (W)	2010	3	21/02/2020
JW023	Sydney Hinterland	Wollemi National Park	6	0-6	2013	2011	2	09/07/2019
JW024	Sydney Hinterland	Yengo National Park	9	0-6	2010	2009	1	09/09/2019
JW025	Sydney Hinterland	Dharawal State Conservation Area	6	7 -29	2014	2001	13	20/02/2020
JW026	Sydney Hinterland	Yellowmundee Regional Park	6	7 -29	2013 (W)	2011	12	10/07/2019
JW027	Sydney Hinterland	Yengo National Park	8	7 -29	2011 (W)	2002	9	10/09/2019
JW028	Sydney Hinterland	Upper Nepean State Conservation Area	6	7 -29	2013	1984	29	12/12/2019
JW029	Sydney Hinterland	Ku-ring-gai Chase National Park	5	7 -29	2015	1990	25	08/01/2020
JW030	Sydney Hinterland	Morton National Park	6	7 -29	2013	2000	13	15/10/2019
JW031	Sydney Hinterland	Wollemi National Park	7	30+	2012	1980	32	12/11/2019
JW032	Sydney Hinterland	Bargo River State Conservation Area	6	30+	2013	1968	45	28/11/2019
JW033	Sydney Hinterland	Ku-ring-gai Chase National Park	10	30+	2010	1979	31	06/01/2020
JW034	Sydney Hinterland	Blue Mountains National Park	9	30+	2011			11/07/2019
JW035	Sydney Hinterland	Cattai National Park	7	30+	2014			17/02/2021
JW036	Sydney Hinterland	Morton National Park	6	30+	2013	1982	31	16/10/2019
JW037	Southern Tablelands	Winburndale Nature Reserve	6	0-6	2013	2008	5	17/07/2019
JW038	Southern Tablelands	Cuumbeun Nature Reserve	6	0-6	2015	2013	2	21/01/2021
JW039	Southern Tablelands	Kosciuszko National Park	8	0-6	2013	2009	4	19/01/2021

Site	Vegetation Class	NPWS Estate	TSF	Range	Fire 1	Fire 2	Interval	Date
JW040	Southern Tablelands	Abercrombie River National Park	7	0-6	2012	2010	2	12/10/2019
JW041	Southern Tablelands	Kosciuszko National Park	11	0-6	2010	2007	3	26/01/2021
JW042	Southern Tablelands	Wollemi National Park	10	0-6	2009	2006	3	21/07/2019
JW043	Southern Tablelands	Winburndale Nature Reserve	5	7 -29	2014 (W)	2002	12	19/07/2019
JW044	Southern Tablelands	Dangelong Nature Reserve	8	7 -29	2013 (W)	1987	26	22/01/2021
JW045	Southern Tablelands	Nangar National Park	11	7 -29	2010	1986	24	15/02/2021
JW046	Southern Tablelands	Brindabella National Park	8	7 -29	2013	2002	11	20/01/2021
JW047	Southern Tablelands	Abercrombie River National Park	6	7 -29	2013 (W)	1998	15	11/10/2019
JW048	Southern Tablelands	Coolumbooka Nature Reserve	8	7 -29	2013	1989	24	25/01/2021
JW049	Southern Tablelands	Woomargama National Park	6	30+	2015	1984	31	18/01/2021
JW050	Southern Tablelands	Wollemi National Park	9	30+	2010	1979	31	20/07/2019
JW051	Southern Tablelands	Winburndale Nature Reserve	6	30+	2013	1971	42	18/07/2019
JW052	Southern Tablelands	Weddin Mountains National Park	6	30+	2013	1974	39	09/10/2019
JW053	Southern Tablelands	Morton National Park	6	30+	2013	1964	49	14/10/2019
JW054	Southern Tablelands	Merriangaah Nature Reserve	6	30+	2013	1939	74	23/01/2021

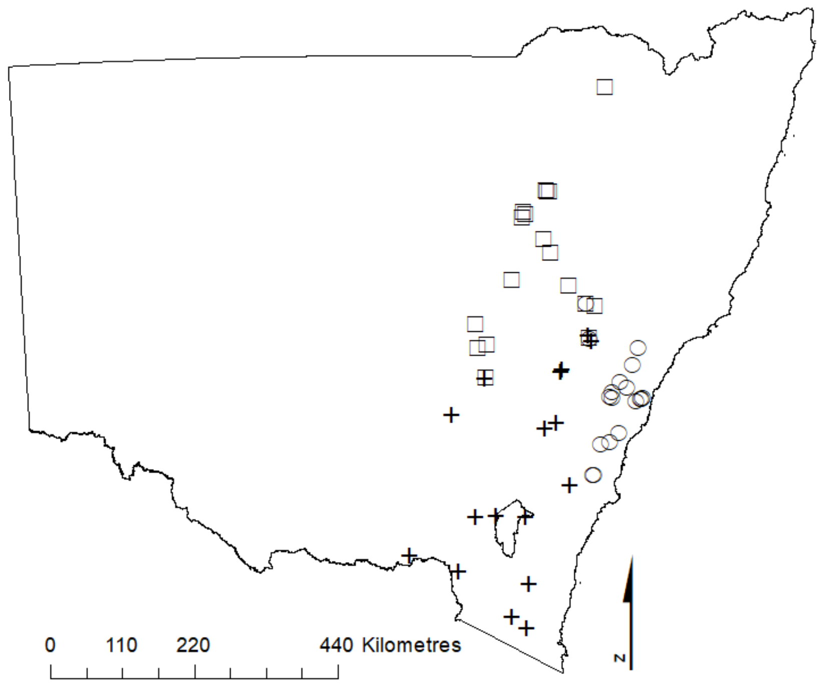


Figure 2.13 Location of field work sites in the Western Slopes Dry Sclerophyll Forests (DSF; square), Sydney Hinterland DSF (circle), and Southern Tablelands DSF (cross) vegetation classes in New South Wales

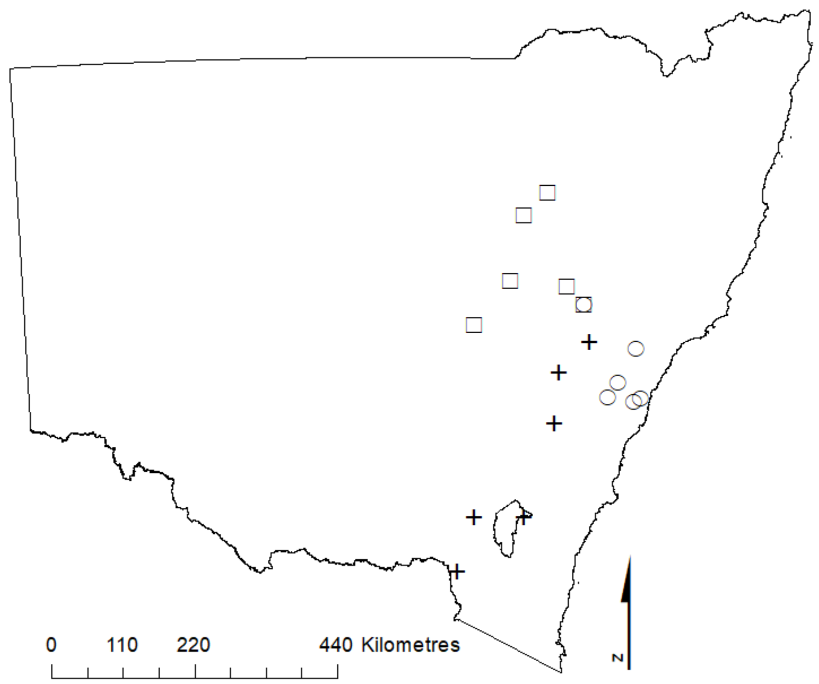


Figure 2.14 Locations of sites with inter-fire intervals between 0 and 6 years in the Western Slopes DSF (square), Sydney Hinterland DSF (circle), Southern Tablelands DSF (cross) vegetation classes

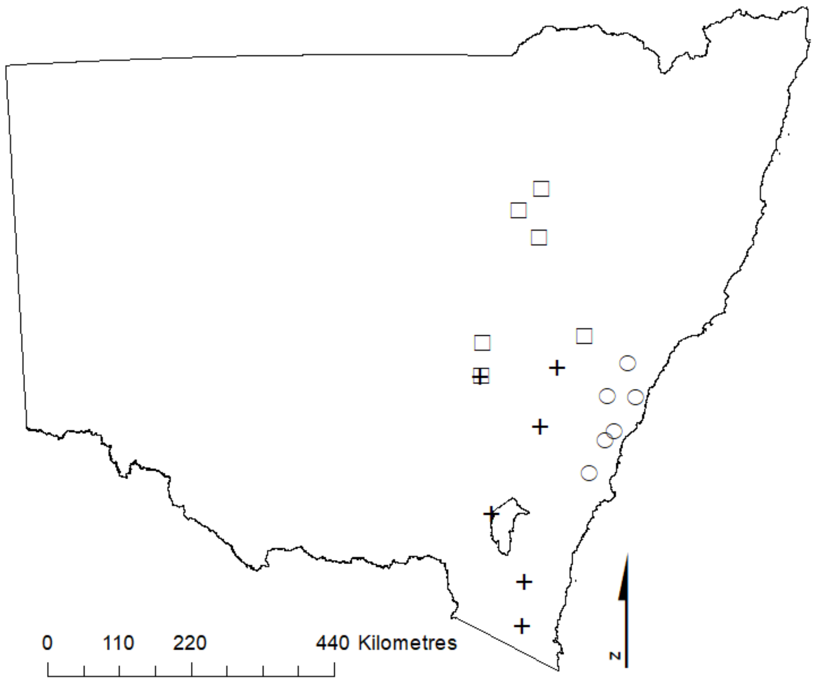


Figure 2.15 Locations of sites with inter-fire intervals between 7 and 29 years in the Western Slopes DSF (square), Sydney Hinterland DSF (circle), Southern Tablelands DSF (cross) vegetation classes

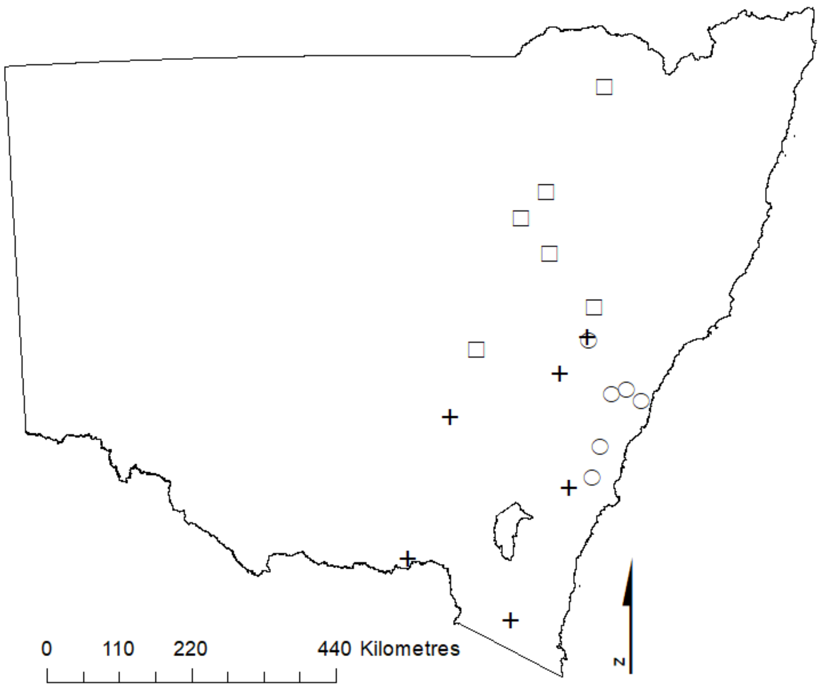


Figure 2.16 Locations of sites with inter-fire intervals ≥30 years in the Western Slopes DSF (square), Sydney Hinterland DSF (circle), Southern Tablelands DSF (cross) vegetation classes

2.5.2 Data Collection

Sampling was undertaken between July 2019 and January 2021, using the reduced sampling regime described in section 2.8.4 (see Table 2.8 for dates). From the habitat attributes collected, a list of habitat variables was derived for analysis (Table 2.9).

2.5.3 Environmental attributes

Environmental, climatic and fire history predictors were calculated for each site (Table 2.10). Climatic variables were obtained from the nearest Bureau of Meteorology weather stations to each site. Slope, aspect, and soil types were calculated in ArcMap (ESRI 2013). Aspect was sine and cosine transformed to obtain a continuous gradient (northness and eastness). Time since the most recent fire, number of known fires, fire type (wild or prescribed) and the number of years between the most recent fire and the fire before that were determined based on information in the digital fire database.

Canopy structure and solar radiation transmittance were calculated from hemispherical images using Gap Light Analyzer software (version 2.0; Frazer *et al.* 1999). For consistency, all images were processed with a pixel intensity threshold of 128.

2.5.4 Grouping habitat variables into habitat types

Given the large number of habitat measurements made (Table 2.9), and the likelihood of correlations among variables, I grouped variables to be analysed to produce a smaller number of derived variables (hereafter termed ‘habitat types’). Individual habitat variables were grouped based on type of variable and published responses of fauna to habitat at different scales (Table 5.2).

Table 2.9. Habitat variables used in analyses

Descriptions of the habitat variables derived from each attribute collected in the field

Variable	Description
Solar radiation transmittance and canopy structure	
Hemispherical photographs	• Percent cover of sky not obscured by canopy
Tree stems	• Total number of trees • Total number of stems • Total number of live/dead stems • Diversity of tree species (Shannon-Weiner Index) • Diameter at breast height (1.3 m; DBH) of largest live/dead tree • Mean DBH • Coefficient of variation in DBH • Number of DBH in five size groups[A] • Total basal area (cm^2) • Mean basal area (cm^2) • Basal area of largest live/dead tree • Total basal area of dead trees (cm^2) • Mean tree height (m) • Height of the shortest tree (m) • Height of the tallest tree (m) • Vertical height range of canopy (m) • Mean scorch height • Total number of scorched stems • Total length of scorch (m) • Total number of stems with epicormic growth • Height above ground of lowest epicormic growth (m) • Total number of basal stems (live/dead) • Height of tallest basal growth • Total stems with decorticating bark • Coefficient of variation of bark type • Total stems with mistletoe[B] • Mean height of lowest live canopy foliage (m) • Total number of stems <15 cm DBH (including basal) • Mean number of stems <15 cm DBH (including basal)
Tree hollows	• Total number of stems with hollows • Total number of hollows • Orientation of hollow entrance • Total of each hollow type • Total number of hollows in five size groups[C]

Variable	Description
Understorey vegetation structure	
Horizontal vegetation density	• Percent of board obscured by vegetation at four heights (0 – 20 cm, 21 – 50 cm, 51 – 100 cm and 101 – 150 cm) above ground • Measured at a coverboard-to-observer distance of 2 m and 5 m in four directions • Mean % at each height and distance
Mid-canopy strata height	• Lowest and highest foliage of tallest plant (stem diameter <15 cm) in three strata groups: Near surface: live foliage 0 cm – 49 cm Elevated: live foliage 50 cm – 99 cm Intermediate: live foliage 1 m – 2 m • Mean height of lowest foliage near surface/elevated/intermediate • Mean height of highest foliage near surface/elevated/intermediate • Total range of near surface/elevated/intermediate vegetation • Total range of mid-canopy height • Height difference between mid-canopy and canopy
Logs and coarse woody debris	
Logs (≥10 cm diameter)	• Total number of logs ≥10 cm diameter • Total length (m) of logs • Mean length (m) of logs • Total length (m) of scorching • Mean proportion of unscorched logs • Total volume (cm^3) of logs • Mean volume (cm^3) of logs • Maximum heigh above ground (cm), measured from ground to highest point • Total length of logs above ground (m) • Total number of stumps • Total diameter at 30 cm of stumps • Mean height of stumps
Log hollows	• Total number of logs with hollows • Total number of log hollows • Total number of hollows in five size groups[C]
Coarse Woody Debris (CWD)	• Total number of CWD • Total length (cm) CWD • Total volume of CWD (cm^3) • Mean volume of CWD (cm^3) • Total length (cm) of scorching • Mean proportion of unscorched CWD

Variable	Description
	• Heigh above ground, measured from ground to highest point • Total number of Clumped (touching ≥3 CWD)/Dispersed (touching ≤ 2 CWD)
Ground cover attributes	
Leaf litter	• Depth of leaf litter (cm) • Weight of wet leaf litter • Weight of dried leaf litter • Moisture loss of leaf litter
Ground Cover	Relative cover of: • living plants • leaf litter (inc. sticks <2 cm diameter) • bare ground • fine woody debris (sticks ≥ and <5 cm diameter) • CWD • logs • rocks • soil crusts • Mean % of each ground cover
Rocks	• Total area (m^2) of rocks with shortest length of ≥5 cm • Mean area (m^2) of rocks with shortest length of ≥5 cm

[A] Diameter at Breast Height (DBH) size groups: 15 – 24 cm, 25 – 34 cm, 35 – 44cm, 45 – 54 cm, ≥55 cm

[B] Mistletoe was only recorded on eight trees and was excluded from analyses

[C] Hollow size groups: 1 – 5 cm, 6 – 15 cm, 16 – 30 cm, 31 – 60 cm, >60 cm

Table 2.10. Variables used as predictors in analyses of variation in habitat among sites

Predictor variable category, variables within each category, and source of data used

Predictor category	Predictor variable	Source
Topography	Slope	Modified DEM-S GIS layer (Dept Planning, Industry and Environment 2019)
	Aspect	
Soils	Great Soil Group	Soil Group (GSG) Soil Type Map of NSW (v 4.5, Dept Planning, Industry and Environment, 2021)
	Hydrologic Soil Groups (high, moderate, slow, and very slow infiltration and water transmission rates)	Hydrologic Groups of Soils in NSW Map (v 3.0, Dept Planning, Industry and Environment, 2017)
Climate	Mean annual rainfall	Australian Bureau of Meteorology 2021
	Total rainfall recorded in the 24 months post fire	
	Total rainfall recorded 2013 - 2020	
	Total spring rainfall (Sept. to Nov.) 2013 – 2020	
	Total summer rainfall (Dec. to Feb.) 2013 - 2020	
	Mean annual temperature	
	Mean annual maximum temperature (MAMT)	
	MAMT spring (Sept. to Nov.)	
	MAMT summer (Dec. to Feb.)	
Fire history	Fire type (wild/prescribed)	NSW fire history database
	Time since most recent fire (TSF)	
	Inter-fire interval	

2.6 Statistical Analysis

2.6.1 Underlying differences among vegetation types and inter-fire interval groups

Given the differences in location, canopy dominants and understorey floristics among vegetation types, there may be inherent differences among the sites that could affect analyses of habitat structure. It was not possible to exactly match the fire history of sites selected in each of the vegetation types and for each of the interval groups. Therefore, prior to further analyses I examined underlying differences in fire history (fire type (wild or prescribed), TSF, and inter-fire interval) among vegetation types and interval groups. I also compared environmental attributes (slope, aspect, mean annual rainfall (MAR), total rainfall in the 24 months post fire (total rain), and mean annual temperature (MAT)) among vegetation types and interval groups. These results guided the selection of predictor variables in subsequent analyses.

2.6.2 Derived habitat types

I used Principal Component Analysis (PCA) in SPSS version 25 (SPSS: IMB Corp. 2017) to derive a smaller number of biologically meaningful habitat types from the habitat variables at a site scale and at quadrat scale (Table 5.2). Data were $\log_{10}$ transformed prior to analyses when required.

The assumptions for PCA were considered to be met if at least one correlation coefficient was >0.3, the overall Kaiser-Meyer-Olkin measure was >0.7, and Bartlett's test of sphericity was statistically significant (P <0.05). Principal components with eigenvalues >1 were considered for retention.

2.6.3 Predictors of differences in habitat

To test for variability in the response of vegetation to fire regimes at different scales and in different vegetation types I analysed data at the site scale and at the finer scale of quadrat. I used Generalised Linear Modelling (GLMs) using the ‘glm’ function in R (R Core Team 2021) to examine the extent to which habitat at a site level was predicted by vegetation type, fire history, and environmental factors. Predictors were selected from among the variables vegetation type, interval group and the environmental and fire attributes listed in Table 2.10 and interactions among these. Response variables were the principal components and eight individual habitat variables that were not well-incorporated into the principal components. As fire management is prescribed at the formation rather than the class level, models were also fitted excluding vegetation type to investigate the influence of the level that vegetation is considered.

Generalised Linear Mixed Models (GLMMs) in R (R Core Team 2021), using the ‘lmer’ function from the ‘lme4’ package (Bates *et al.* 2015), were used to assess the extent to which quadrat-level habitat principal components were predicted by vegetation type, fire history and environment. The ‘lmerTest’ package (Kuznetsova *et al.* 2017) was used to derive the degrees of freedom and p-values for mixed models using transect and site as random effects. Predictors were selected from among the variables vegetation type, interval group, and the environmental and fire variables listed in Table 2.10. The *Poisson* family was used for models of habitat variables that were count data, and *binomial* for variables that were presence/absence. The conditional and marginal R^2 values were calculated using the ‘r.squaredGLMM’ function from the ‘MuMIn’ package (Barton 2020).

For both GLM and GLMM, model selection was based on Akaike Information Criterion (AIC) values. The preferred model was the one with significant predictor variable(s) and the lowest AIC value. Any models with significant predictor variables and with an AIC value not more than two points higher than the preferred model were also reported.

2.6.4 Proximal similarity among sites

I used spatial autocorrelation to test if habitat variables and principal components at sites had a geographically driven pattern irrespective of vegetation types and fire history. Spatial autocorrelation uses a matrix of geographical distances between sites to determine a correlation among values of an attribute weighted by their locational proximities (Diniz-Filho *et al.* 2003). A positive correlation represents similarity in values for geographically nearby sites, and a negative correlation for contrasting values (Legendre 1993).

Spatial autocorrelation was analysed using the Moran's I Autocorrelation Index ('Moran.I' in the 'ape' package (Paradis and Schliep 2019) in R (R Core Team 2021)).

Chapter 3 An assessment of the adequacy of fire records for informing fire management decisions to support biodiversity conservation

3.1 Abstract

Digital fire records for south-eastern Australia for years 1902 to 2018 were used to examine how data quality may affect interpretation of fire history for biodiversity conservation. Thirty-two years and 76% of extant native vegetation in NSW (38% in areas managed for biodiversity conservation) had no fire records, and significantly more in the drier, less populated western parts of the state. Our results indicate this is an incomplete representation of fire history. Repeated records accounted for >50% of the records in the database, however only 8% were identified by an automated clean using software tools. Without a manual-clean the number of fires and area burnt per year would be exaggerated by >300% in some years. The number of repeated records and records with missing data reduced dramatically from the early 2000s. After cleaning, change-point analyses indicate two periods of change in the patterns of recorded area burnt, the mid-1930s and late-1960s, although it remains unclear whether this is a change in fire regime or improved record keeping. Ninety-one percent of records were missing attributes important for biodiversity conservation (month of fire occurrence and intensity), severely limiting the usefulness of the database for biodiversity management, planning, and research.

3.2 Introduction

Understanding fire history is critical to understanding how fire regimes affect biodiversity, making stored data key for management. Fire records are generally stored in written format or spatially in Geographic Information Systems (GIS) and used by management agencies for risk assessment and planning (Hardy *et al.* 2001). Spatial data allow evaluation of patterns including frequency, severity, ignition type, and area burnt (Wittkuhn and Hamilton 2010). Fire data are used to prepare for wild and prescribed fires, allocate resources, forecast fire danger (McArthur 1966,1967), and model changes in fire behaviour due to climate change (Bradstock *et al*. 2012). Using unverified data can lead to misinterpretation of fire trends (Short 2015; Syphard and Keeley 2016).

Error is inherent in spatial data and problems with precision and scale are often unknown and overlooked, resulting in management decisions based on data with unknown levels of uncertainty (Openshaw 1989), recorded at different scales or resolutions, and varying in reliability (Abdelmoty and Jones 1997). Effects of error on interpretation of stored data have been discussed in detail in relation to medicine (Arts *et al*. 2002), climate (Jeffrey *et al.* 2001) and population modelling (Tingley and Beissinger 2009), but less often for ecological fire management (but see Avitabile *et al.* 2013; Short 2015; Syphard and Keeley 2016).

Common sources of error in spatial datasets include incompleteness of records or multiple records of the same data (Brassel *et al*. 1995), location inaccuracy (Goodchild 1995), and logical inconsistencies in relationships among attributes within data (Kainz 1995). Inconsistencies in the amount and type of error in datasets may arise due to sampling bias, uneven collection effort (Yang *et al.* 2013), or data being combined from different sources (Sheeren *et al.* 2009). In biological datasets the number of samples is often positively related to human population density and site accessibility (Reddy and Davalos 2003; Guedes dos Santos *et al*. 2015).

Fire datasets are likely to have similar error and inconsistencies to other spatial datasets. Error may link indirectly to geographic location, population density, or multiple agencies managing for fire (Short 2015), with the attributes recorded potentially varying with fire size and management agency (Filkov *et al.* 2018). However, error in fire datasets might be difficult to detect due to natural variation in fire occurrence among vegetation types, influenced by interactions between climatic conditions and fuels (Flannigan *et al.* 2005; Harris *et al.* 2008).

In the present study I assessed how the quality of digitally stored fire records may affect interpretation of fire history. To do this I used a case study of digitally stored fire records from south-eastern Australia. I aimed to: (1) quantify the number and area of fire records attributable to multiple entries of the same fire and determine the extent of missing information from existing records; and (2) tested for variation in these over time, among vegetation types, and between areas managed for biodiversity conservation and other areas.

3.3 Methods

3.3.1 Study area

The study area was the State of New South Wales (NSW) in south-eastern Australia. Geographically, the 80.1 million ha of NSW is divided into three regions: a thin, coastal strip in the east with a length of 2 137 km; the Great Dividing Range, a complex of mountain ranges, escarpments and plateaus running the length of NSW, ranging in width from 50 to 160 km, and in elevation from 300 to 2 228 m; and the low, western plains, covering almost two-thirds of NSW.

The extant vegetation of eastern NSW is dominated by wet and dry eucalypt forests, with a small area of alpine and sub-alpine vegetation in the south-east, and small areas of rainforests scattered down the east coast, predominantly in the northeast. In the lower, flatter, west, vegetation is sparser and comprised largely of grasslands, semi-arid woodlands and arid shrublands (Keith 2004). In 2010 there were 47.7 million ha of land (60% of NSW) mapped as extant native vegetation within 16 vegetation formations/sub-formations (hereafter 'vegetation formations'), with the remainder designated as cleared (Keith and Simpson 2010). Eight eastern formations had >90% of their area east of the western edge of the Great Dividing Range and six western formations had >90% of their area west of the western edge of the Great Dividing Range (Table 3.1). Widespread formations occurred in both eastern and western NSW (Table 3.1) and were excluded from all east/west comparisons. Six formations were classified as wet based on mean annual rainfall exceeding 900 mm or being dominated by plant species tolerant of periodic inundation or waterlogging (Keith 2004). The ten formations not meeting this definition were classified as dry (Table 3.1).

3.3.2 Data sources

Fire records in NSW are contributed by four main agencies responsible for fire management in vegetated areas: (i) the NSW Rural Fire Service (RFS) responsible for approximately 76.1 million ha (~95%) of NSW; (ii) NSW Fire and Rescue Service, for urban and regional centres; (iii) NSW National Parks and Wildlife Service (NPWS), within NSW Planning, Industry and Environment (DPIE), responsible for 7 million ha; and (iv) NSW Forestry Corporation (2.2 million ha).

Table 3.1. Vegetation formations (Keith 2004) in New South Wales and National Parks and Wildlife Service Estate

For each formation in New South Wales and National Parks and Wildlife Service (NPWS) Estate: total area; percentage with no fire records; year of first recorded fire and number of years with no fire records; percent of records that were replicates; and percent of records missing month or intensity (attributes). Formations classified as wet, dry, east (E), west (W), or widespread (X).

Vegetation Formation	Area in NSW (Mha) (% no records)	Area in NPWS Estate (Mha) (% no records)	Year 1st fire (no. years no fire NSW, NPWS)	% replicate records NSW (NPWS)	% records missing attributes NSW (NPWS)
Dry formations					
DSF (Shrubby) (E)	4.868 (14)	1.867 (14)	1902 (33, 34)	54 (58)	91 (88)
DSF (Shrub/Grassy) (E)	2.601 (30)	0.724 (30)	1903 (41, 43)	55 (59)	91 (88)
Grassy Woodlands (E)	1.897 (22)	0.328 (22)	1935 (37, 41)	53 (54)	89 (81)
Heathlands (E)	0.174 (10)	0.109 (10)	1937 (41, 43)	59 (61)	92 (91)
Alpine (E)	0.152 (25)	0.152 (25)	1938 (61, 63)	48 (49)	75 (75)
Semi-Arid Woodlands (Shrubby) (W)	11.601 (40)	0.685 (40)	1951 (71, 73)	25 (26)	84 (68)
Arid Shrublands (Acacia) (W)	8.842 (82)	0.306 (82)	1957 (99, 103)	29 (44)	92 (69)
Arid Shrublands (Chenopod) (W)	6.968 (95)	0.407 (95)	1973 (97, 100)	9 (5)	51 (18)
Semi-Arid Woodlands (Grassy) (W)	4.755 (96)	0.266 (96)	1951 [A] (81, 92)	24 (36)	91 (68)

Vegetation Formation	Area in NSW (Mha) (% no records)	Area in NPWS Estate (Mha) (% no records)	Year 1st fire (no. years no fire NSW, NPWS)	% replicate records NSW (NPWS)	% records missing attributes NSW (NPWS)
Grasslands (W)	1.337 (76)	0.055 (76)	1938 (59, 63)	52 (61)	90 (86)
Wet formations					
WSF (Grassy) (E)	1.771 (24)	0.576 (24)	1902 (34, 35)	54 (58)	90 (88)
WSF (Shrubby) (E)	1.357 (30)	0.512 (30)	1902 (34, 37)	54 (59)	89 (87)
Rainforests (E)	0.551 (65)	0.311 (65)	1902[B] (35, 39)	58 (61)	90 (89)
Freshwater Wetlands (W)	1.349 (58)	0.074 (58)	1938 (43, 47)	60 (63)	92 (91)
Forested Wetlands (X)	1.014 (59)	0.179 (59)	1902 [B] (33, 35)	56 (62)	90 (88)
Saline Wetlands (X)	0.073 (76)	0.017 (76)	1938 (45, 48)	62 (65)	92 (93)

[E] 90% area east of western edge of Great Dividing Range (GDR); [W] 90% area west of western edge of GDR; [X] both east and west of GDR; [A] first fire in NPWS Estate in 1963; [B] first fire in NPWS Estate in 1903; DSF: Dry Sclerophyll Forest; WSF: Wet Sclerophyll Forest

For this study I used all fire records for NSW stored within four digital datasets, three managed by the RFS and one by NPWS. At the time of the study two RFS datasets contained wildfire records from 2001 to 2018 (hereafter RFS_F1) and 1902 to 2007 (RFS_F2). The third (RFS_HR1) contained hazard reduction records from October 2006 to February 2016. The NPWS dataset (hereafter NPWS_F) contained records of wild and prescribed fires from 1902 to 2016 within NPWS lands. The RFS maintain the central datasets that are the primary source of fire data for wildfire management across NSW. Data in all four datasets are stored in GIS layers as spatial records of reported incidents of wild or prescribed fires, or mechanical hazard reduction (not used in the present study).

Each record used here should represent an individual wild or prescribed fire. Eight of the eleven attributes in the RFS and NPWS_F datasets relevant to these analyses were used (Table 2.3). The remaining attributes were only useful to the agency (e.g., objective met). Not all fire records contained information for all attributes. For each fire record I assigned a unique identifying number that linked it to the original dataset and record. If records did not have a value for year of fire, I assigned a single calendar year based on start or end date. If there was no date, I took the earlier of the two calendar years recorded for season. Thus, for fires with no start or end date, I may have assigned the wrong year e.g., fire season 2002 - 2003, fire year assigned as 2002 but fire occurred in 2003.

3.3.3 Cleaning datasets

Prior to analyses I used a three-step cleaning process. Step one was a pre-clean of each of the four datasets to remove any record which was not a fire or had insufficient attribute information to determine whether it was a fire. The 2605 records (totalling 81 861 ha) that had no attribute information were removed, as these records could not be used in analyses.

The 1841 fire (total of 0.4 ha) records <10m^2 were removed as it was unable to be determined if they were fire suppressed quickly or a data entry error (Table 2.2).

The second step was an automated clean (hereafter auto-clean) using tools in ArcMap (ESRI 2013) to identify replicate records. The 'Find Identical' tool was used to remove replicate records within each dataset. These deleted records were visually checked to ensure they were replicates of a retained record. The 'Are Identical To' option within the Spatial Join tool was then used to find any records with identical year, size (ha) and perimeter (m) between datasets. The polygons for each record identified by the ArcMap tools were visually checked and repeat records of the same fire were removed, whilst retaining all attribute information if spread among multiple records. The four cleaned datasets were then merged into the final database (hereafter database (*a*)).

The final step was a manual-clean of database (*a*) where records were sorted alphabetically by fire name and then year and, after a visual inspection, any polygons with the same fire name and year and overlapping perimeter were merged. Most fires did not have a fire name, so all records were sorted chronologically, and the information icon used to identify multiple layers of records with the same year and the same or similar area and perimeter size, or polygons with the same year and completely contained within another polygon. Any records matching these criteria were merged into one record (unless date information indicated different fires), to create a new boundary covering the maximum possible area for all records of that fire. Where boundaries were slightly different, this process may have inflated the area burnt for some records. Most records did not indicate the month of fire occurrence, so this process may have merged fires that occurred at different times in the same year and burnt within the same approximate perimeter. These criteria for merging may not have recognised replicate records of small fires which were recorded with different coordinate systems or datums and did not overlap.

3.3.4 Land managed for biodiversity conservation

A zoning system is used by authorities to set fire management objectives across NSW. Lands where asset protection is not the primary objective, and fire is used to promote ecological outcomes such as biodiversity conservation, are termed Land Management Zones (LMZs) (Office of Environment and Heritage 2013). Approximately 9.5% of extant vegetation in NSW is set aside as formal reserves, and approximately 10% of privately owned land is managed for conservation (NSW Environment Protection Authority 2018). Although LMZs occur in these and other tenured land, here I used only the 6.5 million ha (14% of extant vegetation) zoned as LMZ on NPWS land (Figure 2.1), where biodiversity conservation is a key legislated objective (NSW National Parks and Wildlife Act 1974).

Fire management varies among the 16 native vegetation formations, based on structure and physiognomy (NSW Rural Fire Service 2021). I used GIS layers of the vegetation formations of NSW (version 3.03, Keith and Simpson 2010), to create 16 separate datasets of fires recorded within each vegetation formation (hereafter non-NPWS). I then used the ‘Clip tool in ArcMap (ESRI 2013) and a GIS LMZ layer to create a further 16 datasets of only the LMZ portion of each formation in NPWS land managed for biodiversity conservation (hereafter NPWS Estate).

3.3.5 Quantifying the error

As a measure of error, I quantified the number of replicate records and the percentage of records missing attributes important for biodiversity conservation (month of fire occurrence and fire intensity) for NSW as a whole and each portion of each vegetation formation in NPWS Estate, and the proportion of each vegetation formation not within NPWS Estate LMZ (hereafter non-NPWS). Using a Wilcoxon-signed rank test I compared the proportion of replicate records identified by the auto- and manual-cleans. I also tested if the median percentage of records missing attributes in a given vegetation formation differed between NPWS Estate and non-NPWS, between eastern and western NSW, or between wet and dry vegetation. As there was only one wet formation in western NSW, wet and dry vegetation was compared for eastern formations only. As the NPWS_F dataset only contained records until 2016 I omitted 2017 −2018 data from all analyses using NPWS Estate data.

There is potential for error in interpretation of fire history due to missing records. I tested if percentages of vegetation formations with no fire records differed between NPWS Estate and non-NPWS, between eastern and western, or wet and dry eastern formations using a two-factor analysis of variance (ANOVA).

In addition, to determine if there were records of fires not in the fire history database, I used a systematic search of newspapers (n = 479) between 1803 and 1969, stored within the online electronic newspaper archive of the National Library of Australia (Trove). For the first 100 articles per year (or all if <100) mentioning bushfires, I recorded details of large fires (>5 ha) within areas mapped as extant vegetation in 2010. I cross-checked if fires were in the database. Full details of methods are in Chapter 2.2.4. No other sources of fire records were examined.

3.3.6 Assessing change in time

Data quality may change at particular points in time due to change in factors that affect record keeping (e.g., legislative or technological change). I used change point analyses to test for temporal patterns in scale and location (Fearnhead and Rigaill 2019) in recorded area burnt, missing attributes, or repeated records. Originally, change point analyses tested for a single change point (Page 1955), but tests for multiple change points in time series data have been developed for use with larger datasets (e.g., economics, Oh *et al.* 2005;

climate change, Reeves *et al.* 2007). Use with small datasets may lead to excess noise, lack of statistical power (Andersen *et al*. 2009), and difficulty determining thresholds for the test statistic, increasing false positive detections (Ross *et al*. 2011). As this database was small (117 data points, years 1902 to 2018), I compared consistency among seven methods in change points detected.

Many commonly used change point tests are parametric, and their assumptions were not always met with database (*a*). Therefore, I used two parametric (one single, one multiple) and five non-parametric (one single, four multiple) methods to detect change points (Table 3.2; see section 2.2.5 for full details of methods). Data for total area burned per year were logarithm_{10}-transformed to reduce skewness and heterogeneity of variance and converted to a time series prior to change point analysis. All change point analyses were conducted in R (R Core Team 2018). Based on the change points identified, I selected subsets of data and used Spearman's correlation to assess change in error over time. Using the same subsets, I tested relationships of number of records and area burnt to time using regression analyses. I used analysis of covariance to compare the parallelism of regression lines of recorded area burnt over time for post-auto-clean and for unique records ('sm.ancova' in the 'sm' package; Bowman and Azzalini 2018 in R, R Core Team 2018).

Wilcoxon-signed Rank tests, two-factor ANOVA, Spearman's correlations and regression analyses were performed in SPSS version 25 (SPSS: IMB Corp. 2017).

3.4 Results

The four datasets originally contained 168 951 records. The cleaning process reduced this to 39 969 unique fire records (total area 30.6 million ha) in database (*a*), with 18 117 records (10.3 million ha) within NPWS Estate. The earliest recorded fires in database (*a*) were in 1902 and the most recent fires used in my analyses were in 2018.

Table 3.2. **Change point methods used in analyses**

For each test: number of change points tested (single or multiple); test type (parametric (P), non-parametric (NP)); and the R statistical package (v 4.0.1) used for analyses

Test	Single/ Multiple	Type	R Package
F-Statistic	Single	P	*strucchange* (Zeileis *et al*. 2002)
Pettit	Single	NP	*trend* (Pohlert 2018)
E-divisive	Multiple	NP	*ecp* (James and Matteson 2014)
Mann-Whitney	Multiple	NP	*cpm* (Ross *et al.* 2011; Ross 2015)
Breakpoint	Multiple	P	*strucchange* (Zeileis *et al*. 2002)
Lepage	Multiple	NP	*cpm* (Ross *et al.* 2011; Ross 2015)
Mood	Multiple	NP	*cpm* (Ross *et al.* 2011; Ross 2015)

3.4.1 Error in the fire datasets

All four source datasets were necessary to capture all fire records because each dataset contained records that were not found in any other dataset. The RFS datasets captured 82% of NPWS records. There were 5837 records in the NPWS_F dataset that were not in the RFS datasets. These records were spread from 1902 to 2016 but most of the area was before 1990 (Figure 3.1). At least 560 records within NPWS Estate were in the RFS datasets but not in NPWS_F, mostly before 2000. The process of merging was responsible for 20 185 (48%) repeated records in the database. Of the remaining 21 908 repeated records, 99% (21 758) were repeats of RFS records within RFS datasets, and 1% (150 records) were repeats within NPWS_F.

Each cleaning stage removed many records. Pre-cleaning removed 86 889 records; 2% were small fires (<10m^2), the remainder were not fires or were missing all attribute information (Table 2.2). The manual-clean removed more than ten times as many replicate records as the auto-clean of the database (auto 3268 records, 2.7 million ha; manual an additional 38 825 records, 34.4 million ha; Figure 3.2*a*). Similarly, in areas managed for biodiversity in NPWS Estate the auto-clean removed 1195 replicate records (1.4 million ha) while the manual-clean removed an additional 22 321 (15.4 million ha; Figure 3.2*b*). Not completing a manual-clean exaggerated the number of fires and area burnt by >300% in some years (Figure 3.2; e.g., Table 3.3). The effect of cleaning was not uniform among vegetation formations and differed between time periods (e.g., Table 3.3), and cleaning eliminated a spurious extreme peak in area burnt in the 1990s (Figure 3.3). The mean percentage of records (± SE) that were replicates was 55% ± 1 in eastern versus 28% ± 6 in western NSW. In eastern dry vegetation this was lower (41% ± 5) than in wet (57% ± 1; Table 3.1).

Of the unique records, 91% (36 521 records), although containing enough information for my analyses, were missing month and/or intensity (Table 2.3**)**. There was no ‘fire type’ attribute in the RFS datasets because RFS_F1 and F2 were dedicated to wildfire records. However, based on comparison with NPWS_F records, there were at least 1350 records of prescribed fires in RFS_F1 and F2 from 1902 – 2006. After commencement of RFS_HR1 in 2006 this reduced to <10 records of prescribed fires per year in RFS_F1 and F2. All records in NPWS_F contained a fire type. Most records were missing a cause of fire and there were inconsistencies within records with an entry for this attribute, e.g., 2% of records in NPWS_F with “cause” listed as lightning had “class” listed as prescribed.

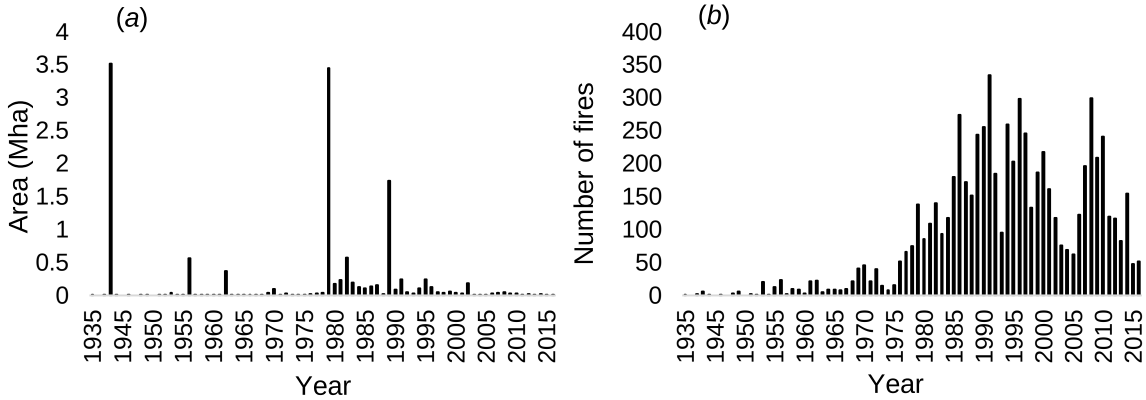


Figure 3.1 (a) Area burnt per year and (b) records in the National Parks and Wildlife Service fire history dataset (NPWS_F) between 1935 and 2016 not recorded in the NSW Rural Fire Service datasets. There were no fire records prior to 1935 found only in the NPWS_F dataset. There were only 4 years between 1935 and 2016 for which all records in the NPWS dataset were included in the RFS dataset.

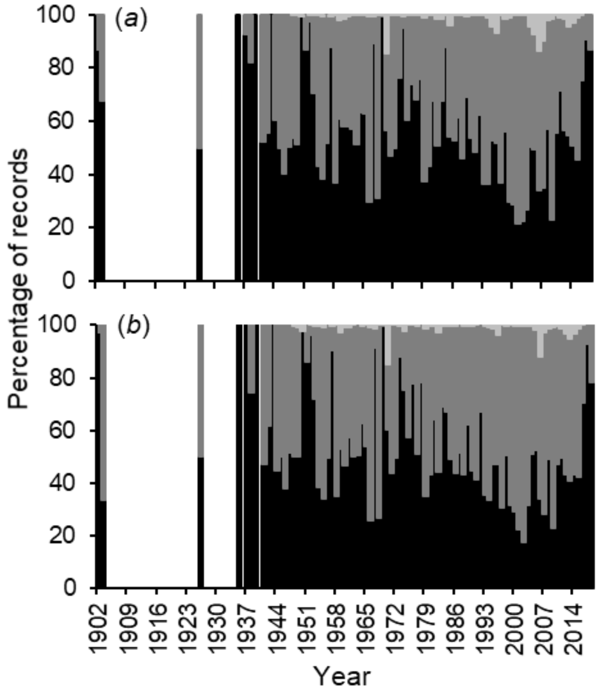


Figure 3.2 Percentage of total fire records in datasets: removed by automated (light grey bars) or manual cleaning (dark grey bars); or retained as unique after cleaning (black bars). Data for (a) all of New South Wales (NSW) and (b) Land Management Zones in NSW National Parks and Wildlife Service Estate. There were 32 years with no fire records

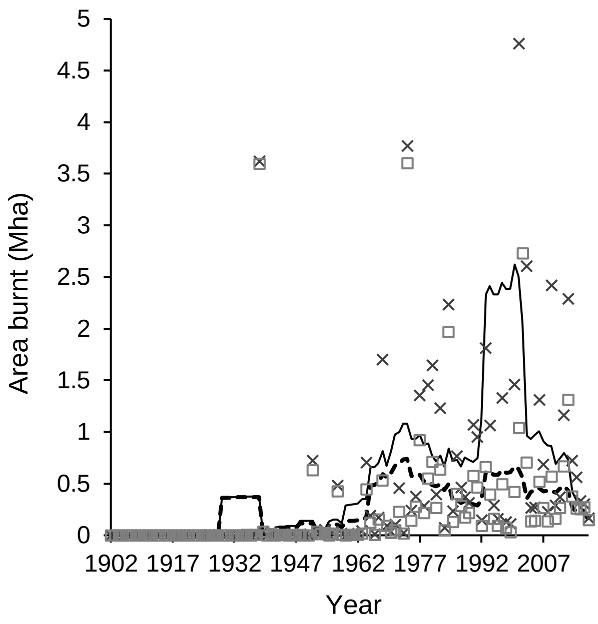


Figure 3.3 Area recorded burnt each year in the New South Wales (NSW) fire history database from 1902 – 2018 after auto-cleaning of the data (x) versus unique records identified by the manual-clean (open square). Ten-year moving average of recorded area burnt each year in the NSW fire history database from 1902 – 2018 based on the auto-cleaning of the records (solid line) versus the manual-clean (dotted line)

Table 3.3. Example impacts of replicate fire records on interpretation of fire history

Number of records and area burnt in two time periods for: Royal National Park (RNP); Blue Mountains National Park (BMNP) within the Blue Mountains World Heritage Area; and for two vegetation formations, Dry Sclerophyll Forest (Shrubby sub-formation) (DSF-S) in eastern NSW and Arid Shrublands (Acacia sub-formation) (AS-A) in western New South Wales. Data shown before any cleaning, after automated cleaning and after manual cleaning

Example	Period	No. fires before cleaning (area (ha))	No. fires post auto-clean (area (ha))	No. fires post manual-clean (area (ha))
RNP	1965 - 2009	1648 (168 082)	1645 (167 058)	603 (51 813)
RNP	2009 - 2018	41 (3507)	41 (3507)	30 (2978)
BMNP	1951 - 2009	1895 (1 546293)	1824 (1 255 530)	722 (473 369)
BMNP	2010 - 2018	276 (168 308)	255 (132 551)	129 (104 915)
DSF-S	1902 - 2009	34 827 (17 078 380)	33 615 (16 003 592)	15 168 (7 141 230)
DSF-S	2010 - 2018	7528 (1 704 088)	7084 (1 458 838)	4794 (1 024 418)
AS-A	1957 - 2009	48 (535 815)	47 (535 704)	40 (535 638)
AS-A	2010 - 2018	188 (201 188)	176 (169 147)	130 (158 004)

3.4.2 Area of New South Wales with no fire records

Between 1902 and 2018, there were no fire records for 76% (37.6 million hectares) of the extant native vegetation of NSW, and 13% (2.5 million ha) of NPWS Estate (Table 2.1). For a given formation, there was a smaller percentage of area with no fire records in NPWS Estate than non-NPWS and in eastern than western formations (2-way ANOVA arcsine transformed: NPWS vs non-NPWS F = 11.537, P = 0.004; east vs west F = 43.306, P <0.0001; interaction F = 1.922, P = 0.185; Table 3.1; Figure 3.4).

Within eastern formations, there was no difference between wet and dry formations in the percentage area with no records, but NPWS Estate had a smaller percentage of area with no records than non-NPWS (2-way ANOVA arcsine-transformed: wet vs dry F = 1.804, P = 0.204, NPWS vs non-NPWS F = 10.125, P = 0.008; interaction F = 2.579, P = 0.134; Table 3.1; Figure 3.4).

However, the database is not an accurate representation of fire history as there is evidence of many fires having occurred that are not recorded in the database. Trove newspaper articles showed that the NSW fire databases are an incomplete record, even for the period spanned by the databases. Of the 13 995 articles dated between 1804 and 1969 examined 546 (4%) reported fires that matched the criteria. Of these, 252 (46%) were between 1902 and 1969, and only four of which were in database (*a*) (Table A2.1). As most articles used adjectives to describe fire size, the area burnt was difficult to ascertain. The earliest fire meeting the criteria was in 1836, 66 years before the earliest fire in the FDB. There were 328 fires (2.3% of articles searched) that may have occurred within lands now zoned LMZ in NPWS Estate.

I found 53 articles reporting fires in western NSW (Table A2.1). These fires, within the Arid Shrublands and Semi-arid Woodland’s formations, occurred in each decade from 1892 to 1969. The earliest reports in Trove of fires in Arid Shrublands were in 1893 compared with 1957 (Acacia sub-formation) and 1973 (Chenopod sub-formation) in database (*a*). The earliest fire in Trove for the Semi-Arid formations was in 1871 compared with 1951 in database (*a*) (Table A2.1).

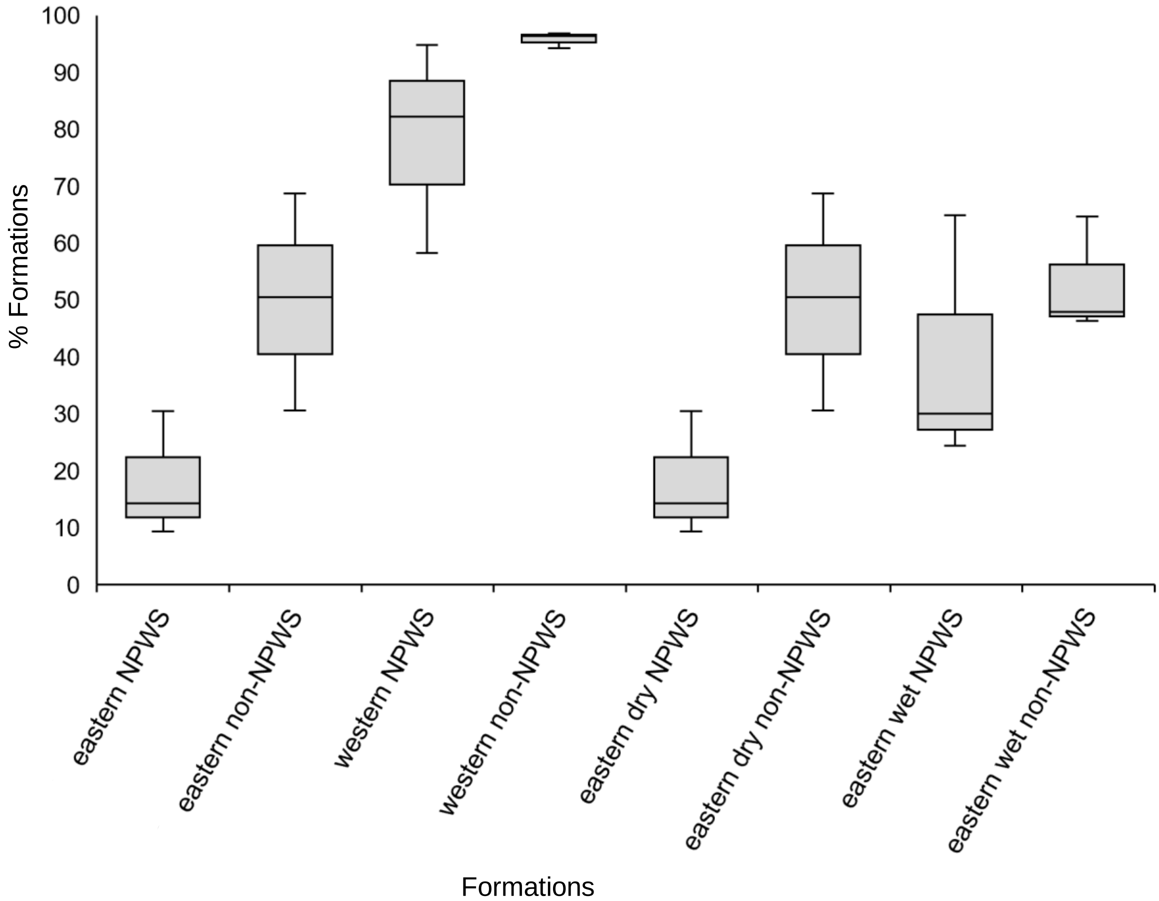


Figure 3.4 Comparison of percentage of vegetation formations with no fire records within New South Wales National Parks and Wildlife Service (NPWS) Estate, and for the proportion of each vegetation formation not within NPWS Estate (non-NPWS). Eastern formations are those with 90% of their area east of western edge of Great Dividing Range (GDR); Western formations are those with 90% of their area west of western edge of GDR (see Table 3.1). The horizontal middle line represents the median value, the shaded box represents the central 50% of data and the lines represent the lower and upper 25% of data

3.4.3 Error within National Parks and Wildlife Service (NPWS) Estate and non-NPWS

For a given formation, NPWS Estate had a larger percentage of replicate records (Wilcoxon: $Z = -2.741$, $P = 0.006$), as might be expected with the merging of the RFS and NPWS datasets. The percentage of records missing month was higher in NPWS Estate than for non-NPWS (Z = -2.585, $P = 0.010$; Figure 3.5). Although missing for the majority of records (Table 2.3), for a given formation the percentage of records missing intensity was lower in NPWS Estate than non-NPWS ($Z = -3.413$, $P = 0.001$; Figure 3.5).

3.4.4 Changes over time

Overall, the number of fire records per year in the database increased over time. The year of first recorded fire and number of years with no fire records varied among formations and the first fire tended to be later in western formations (Table 2.1). Prior to 1957 there were zero to 86 fires recorded per year, 32 years with no fire records, and five years with >50 records. The number of fire records per year increased between 1957 and 1980 (Spearman's correlation $\rho = 0.789$, $P < 0.0001$; range 19 to 781, 19 years >50 records). Between 1980 and 2008, number of records per year was variable but increased gradually (Spearman's correlation $\rho = 0.436$, $P = 0.018$; mean ± SD = 722 ± 214, range 237 - 1165). From 2009 there was a general increase until records peaked in 2013 (from 1713 to 2366 records), with a decline thereafter to 1045 records in 2016.

Two periods of change were identified in the pattern of area burnt per year in NSW: between 1934 and 1937, and between 1962 and 1967 (Figure 3.6*a*). All but one of the change points identified by the multiple change point methods were within the 'strucchange' package confidence intervals (1935 −1937, 1959 – 1967; Table 3.4).

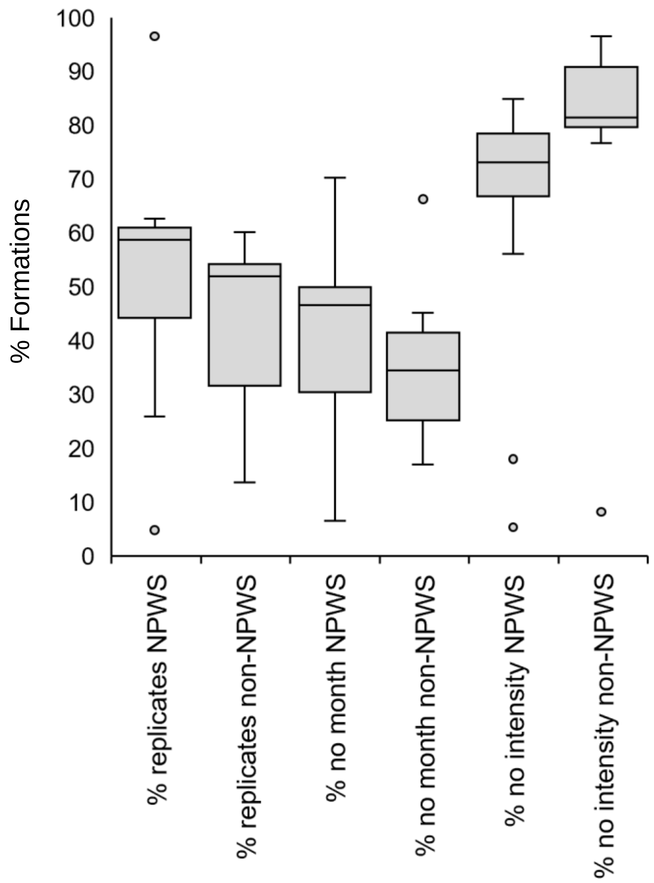


Figure 3.5 Comparison of error and completeness of the NSW fire database within New South Wales National Parks and Wildlife (NPWS) Estate (grey) and proportion of each vegetation formation not within NPWS Estate (white). The horizontal middle line represents the median value, the shaded box represents the central 50% of data and the lines represent the lower and upper 25% of data. Circles designate outliers (points >1.5 times the interquartile range from the upper or lower quartile)

The single change point tests (Table 3.2) each identified one of the two change periods (Figure 3.6*a*). The Mood and Lepage tests consistently identified a change point in 1937, even in formations with no fire records for 20 years either side of 1937. As it was unable to be determined when this was an error (possibly due to small sample size) or a real change point I only report Mood and Lepage results in Appendix 2 (Figure A2.5, A2.7). Within NPWS Estate change points (1936 – 1937, 1961 – 1967) were similar to those identified in NSW as a whole, with an additional change point identified in 1950 by the Pettitt method (Figure 3.6*b*).

For vegetation formations with >500 records, change points were similar to those for NSW as a whole. However, change points for formations with shorter fire history and <500 data points (all in western NSW) were varied and spanned wider ranges, largely 1950 – 1981 and 1997 – 2010 (Figures A2.1 – A2.7). Therefore, the points consistently identified for larger datasets, 1937 and 1967, were used as the points of change in subsequent analyses.

For unique records in the database there was no detectable trend in area burnt per year for 1937 – 1967 (Spearman's correlation: n = 31, ρ = 0.186, P = 0.317), or 1968 – 2016 (Spearman's correlation, n = 49, ρ = 0.146, P = 0.316). For 1968 – 2016 area burnt ranged from 20 382 to 3 605 562 ha (mean ± SD = 501 043 ± 669 226 ha), despite large spikes centred around 1974 and 2001−2002 (Figure 3.3).

Not doing a manual-clean would not change the interpretation of relationships of area burnt over time (ANCOVA post-auto- vs post-manual-clean: 1937 – 1967 h = 5.775, P = 0.541; 1968 – 2016 h = 4.304, P = 0.142). Despite exaggerating the area burnt per year, analysing trends with just the auto-clean did not show an increase in area burnt from

1937 – 1967 (R^2 = 0.013, P = 0.563) or from 1968 − 2016 (R^2 = 0.024, P = 0.280; Figure 3.3).

Changes identified in location and scale of all error types varied but were at similar times to changes in area burnt for NPWS Estate and non-NPWS (1933 – 1946 and 1962 – 1998; Figure 3.7). A third period of change was identified for error (2001 – 2013), but not for area burnt (Figure 3.7). Based on this variation in change points, I analysed error over a range of time spans centred on 1937 and 1967, and the later period of 1992 −2016 (Table 3.5).

The percentage of replicate records increased until 2000 and reduced steeply thereafter in both non-NPWS and NPWS Estate (Table 3.5; Figure 3.7 *a, d*). The percentage of records missing month declined gradually from a peak in the late 1930s until 1999 and then declined steeply to <1% of records from 2014 to 2016 in non-NPWS and NPWS Estate (Table 3.5; Figure 3.7 *b, e*)**.** The percentage of records missing intensity data within non-NPWS areas showed a decline from 1937 to 1965, was variable until 1993 and then increased thereafter (Table 3.5; Figure 3.7*c*) This differed in NPWS Estate which increased from 1937 to 1965, was variable until 1991 and then declined until 2016 (Table 3.5; Figure 3.7*f*).

Table 3.4. Confidence intervals for change points

For the whole of New South Wales and for each vegetation formation/sub-formation, the 95% confidence intervals identified by the Strucchange test for each change point (CP) identified, indicating the years within which a change in area burnt occurred

Formation/sub-formation	CP 1	CP 2	CP 3
All Fires	1935 - 1937	1959 - 1967	
Alpine	1597 – 1963		
Arid Shrublands (Acacia)	1991 – 2003		
Arid Shrublands (Chenopod)	1960 - 1986	1980 – 2022	
Dry Sclerophyll Forest (Grassy/Shrubby)	1924 - 1942	1948 - 1952	1969 - 1977
Dry Sclerophyll Forest (Shrubby)	1935 - 1937	1959 – 1967	
Forested Wetlands	1935 - 1937	1961 – 1965	
Freshwater Wetlands	1934 - 1940	1961 – 1965	
Grasslands	1967 - 1973	1995 – 2007	
Grassy Woodlands	1932 - 1936	1958 - 1962	
Heathlands	1938 - 1944	1960 – 1966	
Rainforests	1934 - 1938	1961 – 1965	
Saline Wetlands	1938 - 1946	1972 – 1978	
Semi-Arid Woodlands (Shrubby)	1965 – 1971		
Semi-arid Woodlands (Grassy)	1965 – 1981		
Wet Sclerophyll Forests (Grassy)	1935 - 1937	1966 – 1974	
Wet Sclerophyll Forests (Shrubby)	1936 - 1938	1967 - 1973	

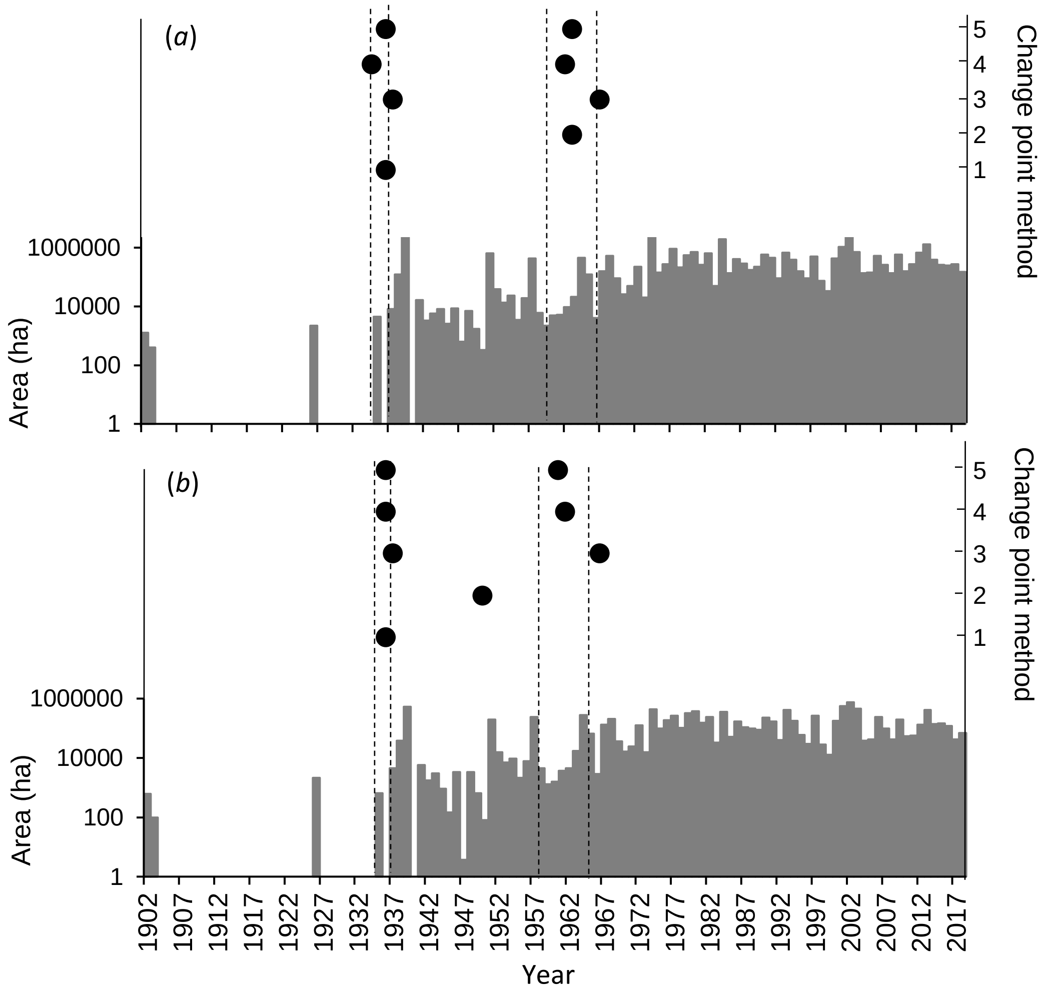


Figure 3.6 Area burnt per year in (a) New South Wales (NSW) and (b) areas managed for biodiversity (National Parks and Wildlife Service (NPWS) Estate). Points of change in area burned (ha) between 1902−2018 detected by five change point methods (black dots): 1: F Statistic (single); 2: Pettit (single); 3: E-Divisive (multiple); 4: Mann-Whitney (multiple); 5: Breakpoint (multiple). Confidence intervals (95%) (vertical dashed lines) shown for: (a) NSW 1935 - 1937 and 1959 – 1967; and (b) NPWS Estate 1935 – 1937 and 1958 – 1966

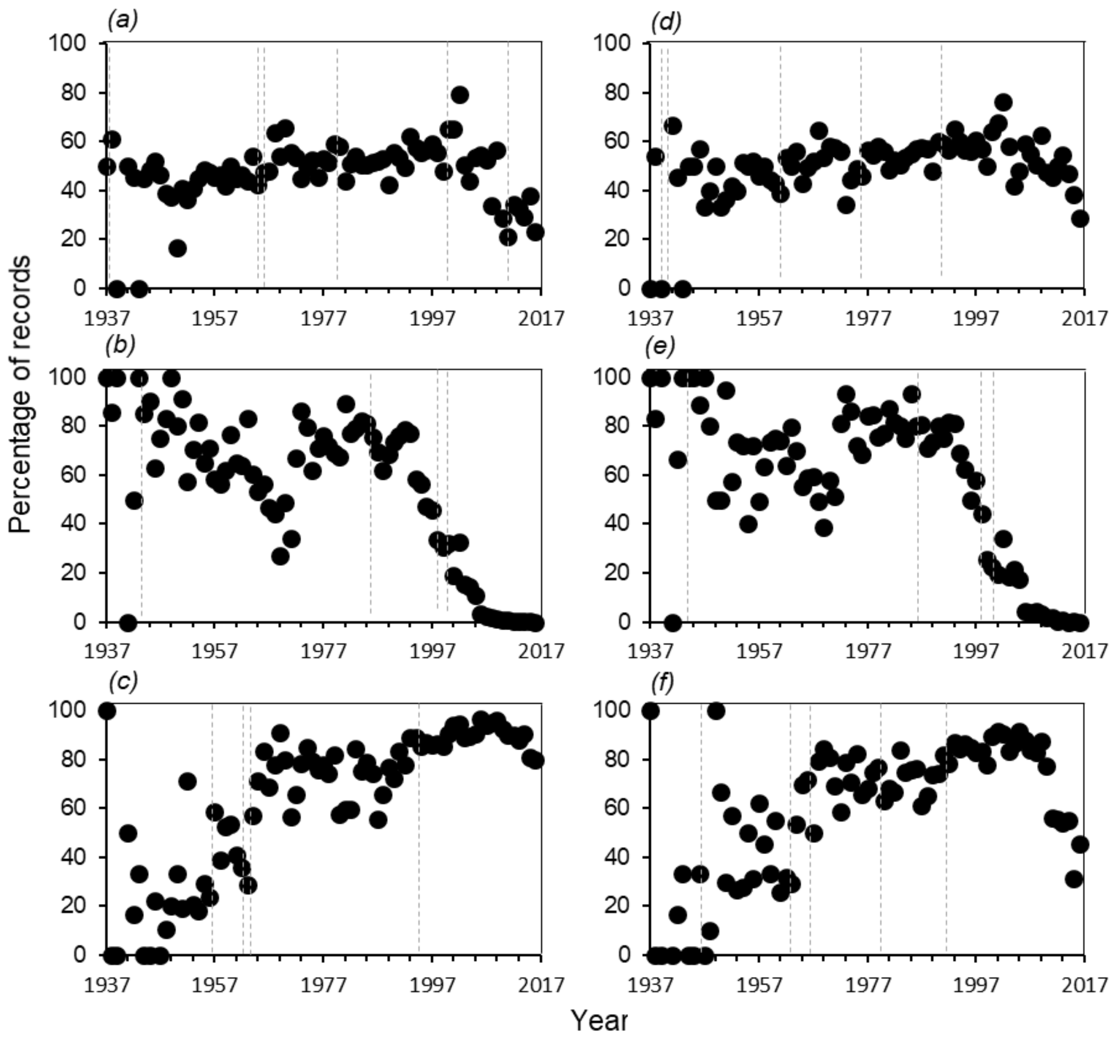


Figure 3.7 Analysis of change over time (1937 – 2016) for percentage of: records in the proportion of each vegetation formation not within New South Wales National Parks and Wildlife Service (NPWS) Estate that were (a) replicates; (b) missing month of fire occurrence; (c) missing intensity; and records in areas managed for biodiversity (NPWS Estate) that were (d) replicates; (e) missing month of fire occurrence; (f) missing intensity. Grey dotted lines indicate change points

Table 3.5. Change in error over time in the New South Wales fire history database

Results of Spearman's correlation (ρ and P-values) examining change over time in percent replicate records, and percent records missing month of fire occurrence or intensity. Results for areas managed for biodiversity conservation (National Parks and Wildlife Service (NPWS) Estate) and other areas of NSW (proportion of each vegetation formation not within NPWS Estate; non-NPWS). Time spans based on change point analyses (see Figure 3.7)

Variable	NPWS Estate / non-NPWS	Time span	Mean ± SD (Range)	ρ	P
% Replicates	non-NPWS	1937 – 2000	48 ± 12 (0 – 65)	0.570	< 0.0001
		2001 – 2016	44 ± 16 (21 – 79)	-0.753	0.001
% Replicates	NPWS	1937 – 2000	49 ± 13 (0 – 67)	0.579	< 0.0001
		2001 - 2016	52 ± 12 (29 – 76)	-0.668	0.005
% Missing month	non-NPWS	1937 – 1999	68 ± 19 (0 – 100)	-0.289	0.023
		2000 – 2016	8 ± 11 (0 – 33)	-0.988	< 0.0001
% Missing month	NPWS	1937 – 1999	71 ± 19 (0 – 100)	-0.164	0.203
		2000 - 2016	9 ± 11 (0 – 34)	-0.969	< 0.0001
% Missing intensity	non-NPWS	1937 – 1966	32 ± 25 (0 – 100)	-0.494	0.008
		1967 – 1991	95 ± 10 (56 – 91)	-0.089	0.652
		1992 – 2016	90 ± 4 (80 – 96)	0.150	0.494
% Missing intensity	NPWS	1937 – 1965	37 ± 29 (0 – 100)	0.446	0.015
		1966 – 1993	72 ± 9 (50 – 85)	-0.045	0.829
		1994 – 2016	77 ± 17 (31 – 92)	-0.515	0.008

3.5 Discussion

This study illustrates a large potential impact on interpretation of fire history due to error in digitally stored fire records. I identified errors in area burnt, and missing attributes which greatly reduce the usefulness of digital records for biodiversity conservation management. Area recorded as burnt was exaggerated if automated software tools were relied on to identify repeated records. There were large gaps in digitally stored fire history, particularly in less populated areas. The amount of error and missing information decreased in the last two decades, particularly in areas managed for biodiversity conservation.

Fire databases around the world are generally similar in structure and content and suffer from similar types of error and inconsistencies (e.g., Africa: Kraaij *et al.* 2013; Belhadj-Khedher *et al.* 2018; North America: Kasischke *et al.* 2002; Short 2014; Syphard and Keeley 2016; Portugal: Pereira *et al.* 2011; Australia: present study): repeated records, missing attribute information, locational bias, and missing records.

Replicate records are typical of large databases integrated from multiple sources (Egenhofer *et al.* 1994) and often occur when fires cross jurisdictional boundaries (Short 2014). However, records due to integrating data from multiple agencies accounted for <50% of the replicates in my study. Replicate records may also occur when daily recording of boundaries is used to measure rate of spread, but previous records are not purged (Pereira *et al.* 2011; a likely scenario in the present study).

Simple automated cleans typically only find exact replicates (Hernandez and Stolfo 1995), and thus fail to identify repeated records not matching in spelling, naming, or digitising (e.g., Short 2014; present study). Therefore, manual cleaning is essential for databases drawn from many sources before data can be used to interpret fire history. Relying purely on an automated clean may grossly exaggerate area burnt (e.g., present study), which could be misconstrued as major change in fire behaviour. Manual cleaning, however, relies on user judgement, which is influenced by expertise and experience, particularly when there are gaps in attribute information (e.g., present study).

Knowledge of fire attributes is critical to biodiversity conservation (Whelan 1995; Bradstock *et al.* 2005). Fire season can affect post-fire responses (Bowen and Pate 1993) and reproduction timing (Taylor *et al.* 1998) in plants, population dynamics and breeding in fauna (e.g., birds: Murphy *et al*. 2010; mammals: Begg *et al.* 1981; reptiles: Greenberg *et al*. 2018), and influences seedling emergence (Knox and Clarke 2006). Fire intensity has direct effects on plant survival, and indirect effects on fauna via changes in habitat structure (Christensen *et al*. 1981; Fox *et al*. 2003). It would be expected that fire records in areas managed for biodiversity would include more of these biodiversity-relevant attributes, but this was not the case in the present study. The between fire interval and interval variability can influence plant species composition and reproduction (Morrison *et al.* 1995; Taylor *et al.* 1998), fauna species composition (Andersen *et al.* 2005; Smith *et al.* 2013), and habitat availability (Weber and Flannigan 1997; Haslem *et al.* 2012). Absence of biodiversity-related attributes severely limit the use of fire databases for analysis of long-term responses of biota to fire regimes. Satellite imagery can be used to fill some of these data gaps (e.g., season, Russell-Smith *et al.* 2007; intensity and severity, Hammill and Bradstock 2006).

Locational bias is common in databases of all kinds (Reddy and Davalos 2003; Guedes dos Santos *et al*. 2015) and may partly explain the lack of fire records in western NSW. Western NSW largely ranges from broad acre agriculture to rangeland grazing, with lower population, and smaller proportions of NPWS Estate, and as such fires are less likely to be attended by fire agencies (e.g., on private property) and may not be in the database. Locational bias in the number of records could also relate to variation among vegetation types in flammability and fire return intervals (Leigh 1994; Nano *et al.* 2012). Given that there were many fires in western NSW not in the database, effects of land use, population density and vegetation type are not easily separated as explanations for fewer records.

Identifying changes in fire regimes is essential for understanding effects of climate change in fire-prone landscapes (Enright *et al.* 2015). Change point analyses have been shown to be useful for identifying temporal change in number of fires and area burned (Greece: Dimitrakopoulos *et al*. 2011; Portugal: Fernandez *et al*. 2014; Spain: Moreno *et al*. 2014; Switzerland: Pezzatti *et al.* 2013), however, most of these studies used a CUSUM technique which is sensitive to outliers, and only one used a non-parametric multiple change point method. Whilst the general agreement among methods in the present study is encouraging for use with fire datasets, these results suggest just one method should not be relied on. Fire datasets are generally smaller than those that the change point analyses were developed for (Ross *et al.* 2011). Multiple change point tests were essential in the present study, as single change point tests did not identify all change points.

Although not a comprehensive list of fires missing from the NSW digital datasets, those identified by my study and in Foley (1947) mean that these datasets are not a reliable avenue for examining long-term trends in fire occurrence in NSW. In the shorter term for NSW there was no directional trend in area recorded as burnt between 1969 and 2016, in contrast to the Australia-wide increase in area burned since 2011 shown by Giglio *et al.* (2013). As such, it is not clear if change points identified here for NSW reflect changes in fire behaviour or changes in record keeping. There is evidence of improved record keeping with reduction in error since 2000. It is not clear if reduced error in recent times is typical of fire databases as most studies assessing the magnitude of replicate records have only reviewed a relatively short time period (e.g., 25 years, Pereira *et al.* 2011; 20 years, Short 2014) and have not assessed change in annual error rates over time.

These results suggest that attributes critical for biodiversity conservation management are not routinely collected and suggest inconsistencies in data collection within and among agencies. Standardised data entry protocols typically reduce these types of inconsistencies in databases (e.g., DNA microarray analysis: Brazma *et al.* 2001; medicine: Carise *et al.* 2001; ecology: Sutter *et al.* 2015). If all agencies had a protocol for defining a unique identifier for each fire, automated searches could efficiently identify replicated records, minimising errors incurred by sharing data among agencies. Ideally standard protocols should include checks for boundary and attribute accuracy; and, to meet biodiversity conservation needs, recording of the month and year of fire occurrence, type of fire (wild or prescription), and an intensity score. The inclusion of an attribute rating the reliability of each record, particularly older records, would allow evaluation of data accuracy. Large multi-agency fire databases in other regions have defined minimum standards for records (e.g., Europe, San-Miguel-Ayanz *et al*. 2012; United States, Short 2014), and a world-wide approach to standardised data collection has been advocated (Duff *et al.* 2014; Filkov *et al.* 2018). Such an approach would solve many of the issues highlighted in this study.

3.6 Conclusions

I have shown that manual cleaning and careful consideration of error are critical to any interpretation of fire history from the NSW digital fire datasets. Knowledge of fire regime characteristics is critical for conservation planning and management, but gaps in the fire history and the extent of missing information from existing digital records severely limits the use of the NSW digital datasets for analysing trends and addressing biodiversity conservation issues. The types of problems identified here are typical of digital databases (e.g., Egenhofer *et al.* 1994; Goldberg *et al.* 2008), but many of the errors highlighted here could be eliminated by use of standard protocols for data entry.

It was unable to be determined if changes in area recorded as burnt and error over time were due to changes in the fire regime or to improved record keeping, however reduced error, particularly in the last two decades, and the extensive historic fires only reported in newspapers suggest the latter. Similarly, I was unable to determine if variations among vegetation type were due to characteristics of the vegetation, other climate factors, or ignition sources. The lack of difference between wet and dry vegetation suggest variations are due to more than the vegetation characteristics. Fire records were not necessarily more comprehensive in areas managed for biodiversity. Some missing attributes could be obtained from historic fire records from a range of sources, building a more comprehensive fire history database (e.g., Wittkuhn and Hamilton 2010; Belhadj-Kedher *et al*. 2018) and increasing its usefulness for biodiversity conservation management.

Chapter 4 Location is a better predictor of time since fire than vegetation type

4.1 Abstract

I examined variation among, and predictors of, distributions of time since the most recent fire (TSMRF) for extant native vegetation in NSW in south-eastern Australia. In 2018, TSMRF varied from 0 to 92 years. TSMRF was skewed to shorter intervals in 2018, 2008 and 1998. In more coastal eastern areas, distributions were skewed to shorter times since fire but were similar among wet and dry vegetation types. In arid and semi-arid areas, distributions were greatly variable but skewed to longer TSF than more coastal areas and were often heavily influenced by one or two large fire events. At a local scale, distributions of TSMRF varied within vegetation types that spanned large geographic areas. At a finer scale still, distributions were similar in locations in close proximity, regardless of vegetation type. Within areas managed for biodiversity conservation, distributions of TSMRF were skewed to shorter times since fire than in general for the vegetation type. Previous fire history, mean annual temperature and rainfall, and land-use were stronger predictors of the distribution of time since fire than proximity to roads and population density.

4.2 Introduction

Fire is an intrinsic, but not uniform, influence on the structure and dynamics of ecosystems around the world (Bond and van Wilgen 1996; Bowman *et al.* 2009). The key drivers of the spatial and temporal arrangement of fires are environmental and climatic conditions, distribution of fuels, and ignition agents (Cary *et al*. 2006; Whitlock *et al*. 2013). Variation in these key drivers lead to heterogeneity in fire patterns within and among vegetation types (Meyn *et al*. 2007; Krawchuk and Moritz 2011).

Interactions among climate, vegetation, and topography influence moisture patterns, determining the amount, distribution, and flammability of fuels (Rollins *et al*. 2002). At a regional scale, fire occurrence follows a productivity gradient. In mesic climates productivity, and therefore fuel loads, are high but fire is limited by fuel moisture (Krawchuk and Moritz 2011). Fire occurrence is highest mid-gradient and infrequent at the drier, less productive part of the gradient where it is limited by connectivity of fuels (Pausas and Bradstock 2007; Krawchuk and Moritz 2011; Lehmann *et al.* 2011). Consequently, fire patterns vary among biomes (French *et al*. 2002; Flannigan *et al.* 2005; Harris *et al.* 2008). The flammability of vegetation varies within ecosystems and thus at a more local scale fire activity would be expected to vary within a biome (Bradstock 2010). At a finer scale, within mesic ecosystems fire occurs more frequently in drier vegetation than in wetter vegetation (Mitchener and Parker 2005).

While geographical variation in climate influences ignition frequency (e.g., lightning ignitions more frequent in mountainous regions: Vazquez and Moreno 1998; Koustias *et al.* 2002), humans have changed the occurrence of fire over time through increased ignition rates, fire suppression, changes to land use and cover, and hence fuel arrangement and availability (Spies *et al.*2004; Marlon *et al*. 2008; Bowman *et al*. 2011). Anthropogenic ignitions are the main cause of wildfires in many regions (e.g., southern Europe: Henderson *et al*. 2005; Alaska: Todd and Jewkes 2006, southern China: He *et al.* 2013) and often increase with proximity to high population densities (Sypahrd *et al.* 2007;

Chas-Amil *et al*. 2013). Conversely, active suppression and fire prevention activities are greater in the wildland-urban interface and may reduce fire frequency (Cohen 2000).

Time since fire and the associated changes in vegetation structure are critical to biodiversity management because they influence the suitability of habitat for faunal species (Monamy and Fox 2000; Fox *et al.* 2003). Spatially variable fire regimes in the landscape provide a variety of options to enable persistence of a range of taxa (Bradstock *et al.* 1995; Panzer 2003; Fuhlendorf *et al.* 2006), thereby increasing species diversity. The complexity of factors which influence the burning of vegetation result in natural variation of fire intervals, severity, and extent in the landscape (Bradshaw *et al.* 1997; Beaty and Taylor 2002; van Wilgen *et al.* 2010). Too frequent burning however, while reducing the risk of uncontrolled wildfires (Bradstock *et al.* 1998), can lead to homogenisation of vegetation age classes with negative consequences for biodiversity (Morrison *et al.* 1995; Dellasala *et al.* 2004).

In landscapes managed for biodiversity conservation, variation of fire regimes can be achieved by creating patches of differing fire history and vegetation successional stages (Richards *et al*. 1999). Fire interval thresholds for biodiversity conservation, which guide the targets for proportions of the landscape in any given state, can be calculated in a number of ways including fuel biomass (e.g., South Africa: Brockett *et al.* 2001; van Wilgen *et al.* 2008), natural fire intervals and age class distributions (e.g., Sweden, Angelstam 1998; Australia: Woinarski and Winderlich 2014), or flora life history traits and responses to fire (e.g. Australia: Burrows and Abbott 2003; Kenny *et al.* 2003). However, these are often implemented at a broad vegetation scale (e.g., Kenny *et al.* 2003), whereas variations in fire regimes have been shown to be strongly associated with local topography, climate (Beaty and Taylor 2001; Hellberg *et al.* 2004; Flatley *et al.* 2011), soil and geological features (Fensham and Kirkpatrick 1992; Keith 2011).

Given the influence of interactions among climate, vegetation, and topography on fuel availability and fire occurrence, at any given point in time it would be expected that: (1) distributions of time since fire would be skewed to longer intervals in moister vegetation than drier vegetation types; (2) this relationship should hold at a broad landscape scale and at finer scales; (3) time since fire will not be evenly distributed within a vegetation type; and (4) these relationships will be moderated by landscape management actions that influence ignitions. The aim was to test these predictions using fire history records for extant vegetation in south-eastern Australia.

4.3 Methods

4.3.1 Study area

The study area was the State of New South Wales (NSW), occupying 80.1 million ha in south-eastern Australia. Geographically, NSW is divided into three regions: a thin, coastal strip in the east with a length of 2137 km; the Great Dividing Range, a complex of mountain ranges, escarpments and plateaus running parallel to the coast, ranging in width from 50 to 160 km and in elevation from 300 to 2228 m; and the low, western plains, which cover almost two-thirds of the State.

The climate of NSW is spatially and temporally variable. In the mesic east the climate ranges from cool in the south with uniform rainfall through the year (mean annual rainfall 600-1500 mm) to humid and sub-tropical in the north with high summer and low winter rainfall (mean monthly rainfall winter 200-400 mm, summer 400-800 mm; Bureau of Meteorology 2020*a*). The Great Dividing Range enhances rainfall near the coast and contributes to the main environmental gradient running from the temperate east (mean annual rainfall 600 - 2000 mm, warm summers and cold winters, mean annual temperature range 9 – 24^{o}C) to the semi-arid and arid west (mean annual rainfall 100 - 500 mm, hot dry summers and cold winters, mean annual temperature range 12 – 27^{o}C) (Bureau of Meteorology 2020*a, b*). The alpine and sub-alpine regions of the Great Dividing Range in southern NSW experience high winter rainfall and dry summers (mean annual rainfall 1000-2000 mm, mean annual temperature range 6 – 12^{o}C) (Bureau of Meteorology 2020*a, b*).

4.3.2 Vegetation types

Areas mapped as extant vegetation in 2010 (49.5 million ha, 62% of NSW) were used in the study, and areas mapped as cleared excluded (30.6 million ha) (Keith and Simpson 2010). The extant vegetation of eastern NSW is dominated by wet and dry eucalypt forests, with a small area of alpine and sub-alpine vegetation in the south-east, and small areas of rainforests scattered down the east coast, predominantly in the north east. West of the Great Dividing Range vegetation is comprised largely of grasslands, open woodlands and arid shrublands (Groves 1994).

Extant vegetation of NSW is classified into 16 formations or sub-formations (hereafter together referred to as ‘formations’), based on structure and physiognomy (Keith 2004; Table 2.1). The 16 formations are further subdivided into 103 classes based on structural and floristic characteristics (Keith and Simpson 2010; see Table A3.1 for details of classes). These formations and classes are the ‘vegetation types’ of the study. I classified each vegetation type as eastern, western or widespread (Table 2.1). Eastern vegetation types had >90% of their area east of the western edge of the Great Dividing Range and western vegetation types had >90% of their area west of the western edge of the Great Dividing Range). Widespread vegetation types occurred in both eastern and western NSW (Table 2.1) and were excluded from all east/west comparisons. Vegetation types were further classified as ‘wet’ based on mean annual rainfall exceeding 900 mm or being dominated by plant species tolerant of periodic inundation or waterlogging (Keith 2004). Vegetation types not meeting this definition were classified as ‘dry’. Of the 60 classes within eastern formations, 58 were classified as eastern and two were widespread. Of the 35 classes within western formations, eight were eastern, 24 western and three widespread. Of the eight classes within widespread formations, seven classes were eastern, and one was western.

Vegetation formations varied more than 150-times in areal extent (Table 2.1). The arid and semi-arid formations combined extend ~800 km from west to east and ~700 km from north to south. The eastern formations are restricted to the eastern ~550 km of NSW and combined, extend the ~950 km from north to south. The dry and wet sclerophyll forests and grassy woodlands formations extend over most of the ~950km range, whereas the Alpine, Rainforest and Heathlands formations have a patchy distribution, with Rainforests and Heathlands largely restricted to the east coast.

4.3.3 Management zoning

Authorities use a zoning system to set fire management objectives across NSW. Lands where asset protection is not the primary objective, and a key use of fire is to promote ecological outcomes such as biodiversity conservation, are termed Land Management Zones (LMZs) (Figure 2.1; Office of Environment and Heritage 2013). Approximately 13.4% (10.7 million ha) of NSW is managed for biodiversity conservation, either informal reserves (9.5%) or private lands (3.9%; NSW Environment Protection Authority 2018). The NSW National Parks and Wildlife Service (NPWS) is responsible for over 7 million hectares (9% of NSW) of land within NSW, including 6.5 million ha within LMZs. Although LMZs occur in these and other tenured land, here I used only the 6.5 million ha

(14% of extant vegetation) zoned as LMZs in NPWS land (hereafter NPWS_LMZ; Figure 2.1).

4.3.4 Fire data

All digitally stored records of fire in extant vegetation in NSW in datasets managed by the NSW Rural Fire Service (RFS) and the NSW Office of Environment and Heritage (OEH; now Department of Planning, Industry and Environment) were used in the analyses. The datasets contained details of fires recorded in NSW from 1902 to 2018. I merged all datasets into the one database (database (*a*)) and removed all replicate records and non-fire records (see Chapter 2.2 for details).

The database (*a*) contained 36 176 unique records of fires in extant vegetation from 1902 to 2018. The ‘Count Overlapping Polygons’ (Honeycutt 2012) tool in ArcMap (ESRI 2013) was used to define the boundaries of each area with a fire history different to neighbouring areas. This resulted in 451 684 polygons within extant vegetation with unique fire histories, ranging in size from 0.000007 m^2 to 156 795 6 ha. From these I removed 110 515 records (109 ha) that were Polygons <50 m^2 because they were likely an artefact of boundary recording errors, as most occurred along road edges and shorelines.

For each of the remaining 341 169 polygons I calculated the number of years between June 2018 and the most recent fire in that polygon. The earliest year of the most recent fire for any polygon was 1926. I used GIS layers of the vegetation formations and classes of NSW (version 3.03, Keith and Simpson 2010) to create datasets of fires recorded within each vegetation type. Seven classes were excluded from analyses because they had <42 ha of fire recorded or only had fire records for one or two years (see supplementary materials for details of classes). I then used a GIS layer of LMZs (supplied by OEH, 2018) to create datasets of fires recorded within only the LMZ portion of each formation and each class in NPWS land. The same process was used to create layers for the most recent fires in 2008 and 1998.

I used a GIS layer of the 18 Interim Biogeographic Regionalisation for Australia (IBRA) bioregions in NSW (Dept. of Agriculture, Water and the Environment 2020) to create datasets of fires recorded within each portion of each vegetation type, and the portion within LMZs, in each bioregion (see Table A3.2 for details).

4.4 Data analysis

4.4.1 Distributions of time since the most recent fire

To examine patterns of skew towards shorter or longer fire intervals I calculated the cumulative proportion distributions (C_TSMRF) of the area with the most recent fire in, or prior to each year to 2018, and separately to 2008 and to 1998. To examine the synchronicity of fire occurrence among different areas, I created time since most recent fire (TSMRF) distributions by calculating the proportion of extant vegetation with the most recent fire in each year from 1926 to 2018, and separately to 2008 and to 1998. Both distributions were created for each vegetation type, and for the NPWS LMZ portion and proportion of each vegetation formation not within NPWS Estate LMZ (hereafter non-NPWS) of each vegetation type.

Using a one-way Analysis of Similarity (ANOSIM) I compared the skewness and synchronicity of timing of the most recent fire events among vegetation types in NSW as a whole, within NPWS LMZs, and for non-NPWS. Data were fourth root transformed prior to calculating Bray-Curtis similarity matrices. Hierarchical cluster analyses were used to determine the similarity of distributions among formations (regional scale) and among classes (local scale). For a finer scale I compared distributions among the portions of each vegetation type within the six eastern bioregions on the thin coastal strip east of the Great Dividing Range: New England Tableland; NSW North Coast; South East Corner; South East Highlands; South East Queensland; and Sydney Basin. There were insufficient fire records in the other bioregions to include them in these analyses.

4.4.2 Management and time since fire

Within NPWS LMZs, guidelines for ecological fire management aim to ensure that each vegetation formation has a range of post-fire ages, based on plant responses to fire, aimed at conserving vascular plants and threatened fauna (Kenny *et al.* 2003). The guidelines identify for each formation/sub-formation: a minimum interval, aimed at avoiding loss of plant species or localised decline due to too frequent fire; and a maximum interval, aimed at avoiding loss of species due senescence of plants and stored seed. It is recommended that at least 50% of a formation has a time since the most recent fire between the minimum and maximum intervals, less than 35% below the minimum interval, and less than 35% above the maximum interval (Office of Environment and Heritage 2013). Four vegetation formations have the recommendation that deliberate burning should be avoided: Alpine, Arid Shrublands (Chenopod sub-formation), Rainforests and Saline Wetlands (Kenny *et al*. 2003).

To determine if distributions of time since fire were within the intervals recommended by guidelines for each vegetation formation (Kenny *et al.* 2003; Office of Environment and Heritage 2013), I used ANOSIM to examine how distributions of time since fire within NPWS LMZ and non-NPWS compared to the most diverse range of time since fire distribution achievable, based on fire management guidelines (Kenny *et al.* 2003; Office of Environment and Heritage 2013).

I calculated C_TSMRF distributions with the greatest diversity of time since fire spread over 92 years and within the recommended interval for each formation. For example, a formation with recommended intervals of minimum 5 years and maximum 50 years would result in 35/5 = 7% of the formation at each of 1 to 5 years since fire; 50/45 = 1.1% at each of 6 to 50 years since fire; and 35/42 = 0.8% at each of 51 to 92 years since fire. I used ANOSIM to compare C_TSMRF distributions for each vegetation formation with the most diverse distributions achievable under current fire management guidelines (hereafter Guidelines). I then used a Bray-Curtis similarity matrix to compare distributions of classes to the Guideline for their respective formations. I then tested whether distributions of time since fire (C_TSMRF) for the NPWS LMZ portion of each vegetation type differed to the to the non-NPWS portion using a Kolmogorov-Smirnov test (ks.test; R Core Team, 2020).

I tested if the C_TSMRF distributions among classes were similar within the NPWS LMZ and non-NPWS portions of each formation. For each year of the 92-year fire history I subtracted the cumulative proportion of area burnt within NPWS LMZ from that burnt in non-NPWS. I then calculated the sum of the difference for each class and compared the median difference for each class within a formation.

4.4.3 Predictors of the distributions of time since fire

I used BEST analysis to examine the relative importance of 13 variables as predictors of distributions of time since fire (Table 2.4). BEST analysis was used to find the best match between Bray-Curtis similarity matrices of time since fire and Euclidian distance matrices for environmental predictor variables (Clarke and Ainsworth 1993).

For the portion of each vegetation type within the six eastern Interim Biogeographic Regionalisation for Australia (IBRA) bioregions in NSW (Dept. of

Agriculture, Water and the Environment 2020) I calculated predictors for temperature, precipitation, and human population density using the zonal statistics tool in ArcMap (ESRI 2013; Table 2.4).

The number of human-caused wildfires have been found to be highest within 5 km of roads and trials (Pew and Carson 2001). As a measure of proximity to ignition sources I buffered the portion of each vegetation type within a bioregion by 5 km and divided it into 200 m grid cells. I calculated the distance to the nearest road or fire trail for the centre point of each grid cell in ArcMap (ESRI 2013; Table 2.4) and calculated a mean distance for each vegetation type within the bioregion.

The six land use predictors provided another measure of proximity to ignition sources and were calculated as the percentage of each vegetation type within each land use category (Table 2.4). The percentage of each vegetation type with two, with three, and with four previous fires recorded were used as predictors of the relative importance of fire history in determining the distributions of time since fire. There were not enough fire history data to calculate more than four previous fires.

ANOSIM and BEST analysis were conducted using PRIMER v7 (Clarke *et al.* 2014). The Kolmogorov-Smirnov tests were conducted in R (R Core Team, 2020).

4.5 Results

In 2018, 24% (11.8 million ha) of extant vegetation in NSW had fire records (Table 2.1). Of the area with fire records, 38% was in western and 60% was in eastern formations, 80% in dry and 20% in wet formations (Table 2.1). Except where stated, all analyses and results include only areas of extant vegetation with fire records.

The proportion of each formation zoned as NPWS LMZs varied greatly (3 – 89%) but was lower in western (3 - 6%) than eastern (17 - 89%; 3 with >50%) formations (Table 2.1). The proportion also varied among classes (0.4 – 94%) and was lower in western classes (0.4 – 16%) than eastern (4 – 94%; 27 with >=50%; Table 2.1).

Within extant vegetation in NSW and NPWS LMZ, time since the most recent fire in 2018 ranged from 0 (burnt early 2018) to 92 years (last burnt in 1926). Of the area with fire records, 95% (11.6 million ha) had the most recent record within the last half of the 92-year span of fire history (1973 – 2018; 96%, 3.9 million ha for NPWS LMZ). The most recent fire for 5.3 million ha (8%) of NSW and 1.2 million ha (18%) of NPWS LMZ was in just four of the 92-year span of the fire history (5, 16, 34 and 44 years prior to 2018). For all vegetation formations the most recent fire was recorded in 2018, except for Alpine, which was in 2016.

Time since the most recent fire was skewed to shorter intervals in both NSW as a whole and within NPWS LMZs in 2018, 2008 and 1998 (C_TSMRF; Figure 4.1*a* - *c*). The skew to shorter intervals within NPWS LMZ was markedly greater than for elsewhere in NSW (Figure 4.1*a* - *c*), however was more similar to the NSW and non-NPWS distributions in 1998 (Figure 4.1*c*). A greater proportion of NPWS LMZ consistently had distributions skewed to shorter times than non-NPWS however the magnitude fluctuated through time (Figure 4.1*d*).

4.5.1 Effects of scale

I used data for vegetation formations to examine distributions of time since fire at a regional scale, vegetation classes within a formation to examine local scale, and six eastern bioregions occurring in a thin coastal strip to examine at an even finer scale.

At a regional scale, distributions of time since the most recent fire showed a similar pattern of skew to shorter intervals for seven of the eastern, one western and two widespread formations (Figure 4.2). Overall, eastern formations differed from (C_TSMRF; ANOSIM; Table 4.1), were skewed to shorter intervals than (Figure 4.2; A3.1 – A3.4) and were not synchronous with western formations (Figure 4.3 (*a*); Figure 4.4) at the three time periods tested.

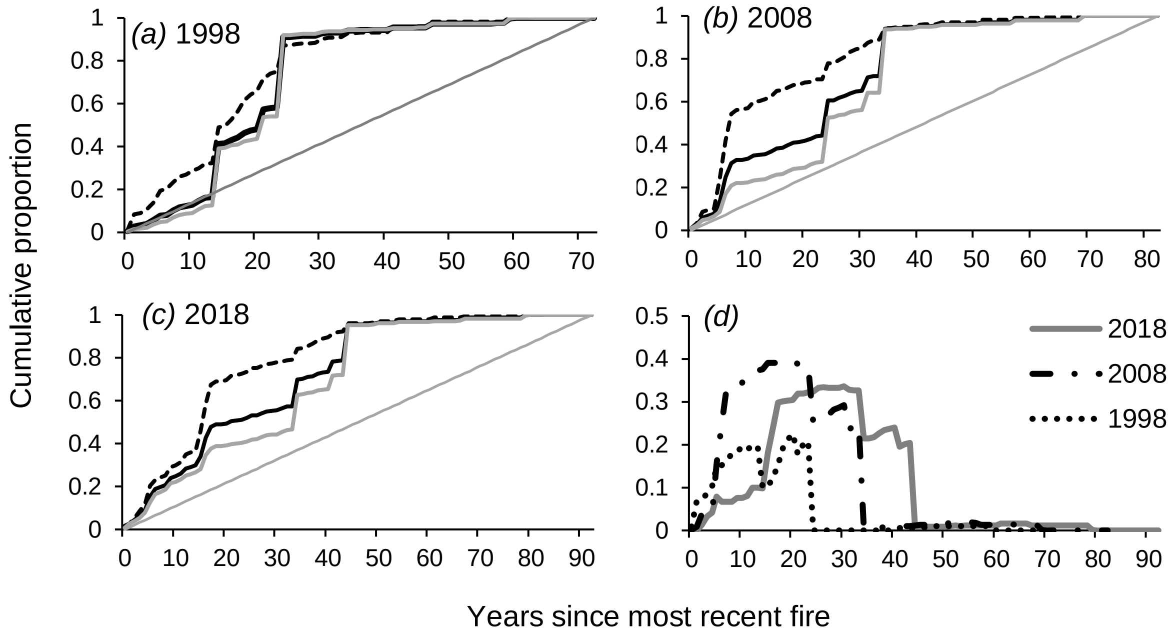


Figure 4.1 Cumulative proportion of most recent fires in each year of known fire history for extant vegetation in New South Wales (NSW) (black line), the proportion of each vegetation type within NSW National Parks and Wildlife Service (NPWS) Estate Land Management Zones (LMZ) (black dotted line), and proportion of each vegetation formation not within NPWS Estate LMZ (non-NPWS) (grey line) in (a) 1998, (b) 2008, and (c) 2018, and (d) the difference in cumulative proportion burnt between NPWS LMZ and non-NPWS for 1998 (black dotted line); 2008 (black dashed line); and 2018 (grey line). The diagonal lines represent an even distribution

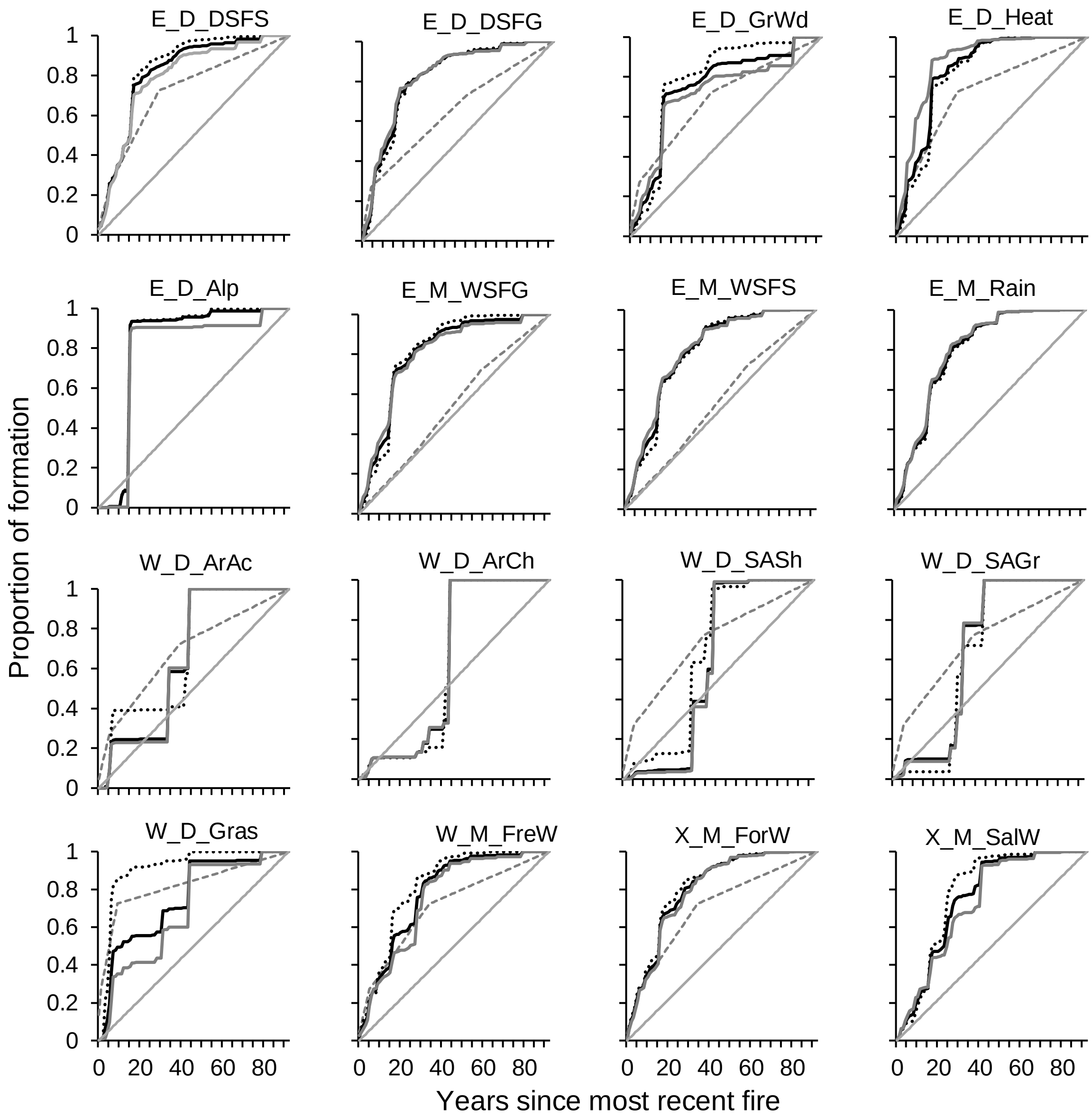


Figure 4.2 Cumulative proportion of most recent fires in each year of known fire history from 2018 (0 years) to 1926 (92 years) for extant vegetation in New South Wales (NSW) (black line), the proportion of each vegetation type within NSW National Parks and Wildlife Service (NPWS) Estate Land Management Zones (LMZ) (black dotted line), and proportion of each vegetation formation not within NPWS Estate LMZ (non-NPWS) (grey line). The diagonal grey lines represent an even distribution, and the grey dotted lines represent the most diverse distribution achievable under management guidelines (Kenny *et al.* 2003). See Table 2.1 for vegetation abbreviation name explanations

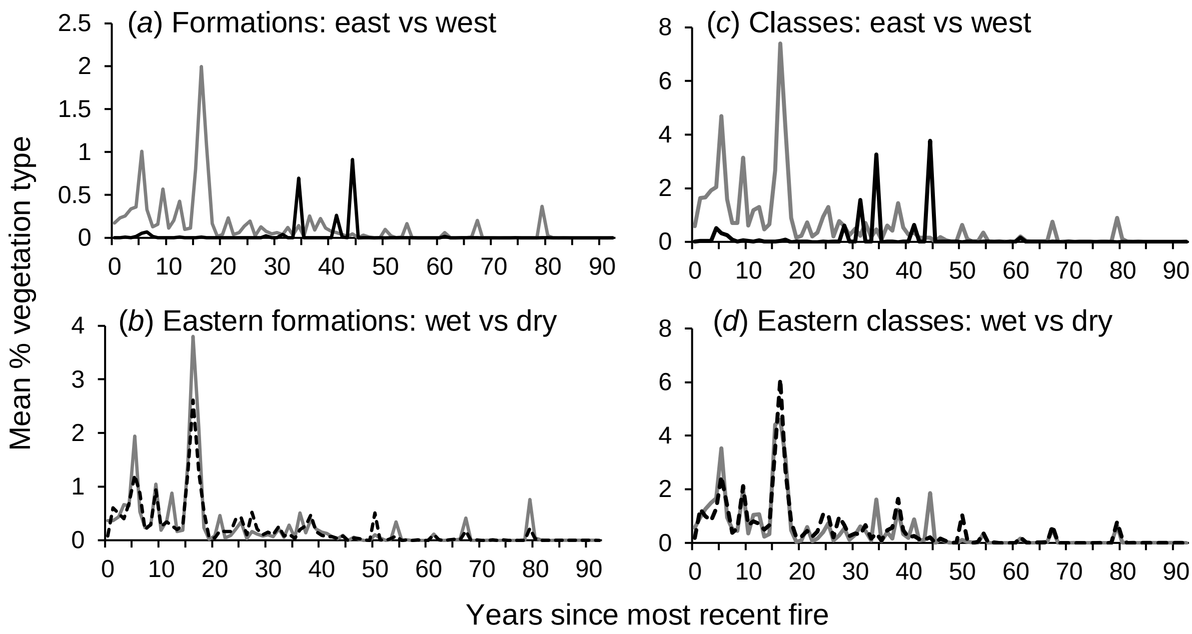


Figure 4.3 Mean percentage of area (ha) of most recent fires in each year of known fire history from 2018 for eastern (grey line) and western (black line) (a) formations and (c) classes; and eastern dry (grey line) and eastern wet formations (black dotted line) (b) formations and (d) classes in New South Wales

Table 4.1. Comparisons of time since the most recent fire distributions among vegetation types in New South Wales

Results of analysis of similarity (ANOSIM) (R and *P* values) comparisons of Time Since the Most Recent Fire (TSMRF) and the cumulative TSMRF (C_TSMRF) distributions for eastern versus western and wet versus dry formations and classes within New South Wales and the proportion of each formation within NSW National Parks and Wildlife Estate Land Management Zones (NPWS LMZ)

Comparison	Distribution type	Time span	NSW R (*P*)	NPWS LMZ R (*P*)
Eastern vs Western formations	C_TSMRF	2018 – 1926	0.54 (0.002)	0.412 (0.006)
		2008 - 1926	0.755 (0.0003)	0.535 (0.002)
		1998 - 1926	0.358 (0.009)	0.289 (0.002)
	TSMRF	2018 – 1926	0.891 (0.0003)	0.053 (0.001)
		2008 - 1926	0.741 (0.0007)	0.497 (0.0002)
		1998 - 1926	0.749 (0.0007)	0.501 (0.002)
Eastern vs Western classes	C_TSMRF	2018 – 1926	0.529 (0.0001)	0.636 (0.0001)
		2008 - 1926	0.751 (0.0001)	0.765 (0.0001)
		1998 - 1926	0.378 (0.0001)	0.552 (0.001)
	TSMRF	2018 – 1926	0.904 (0.0001)	0.81 (0.0001)
		2008 - 1926	0.87 (0.0001)	0.799 (0.0001)
		1998 - 1926	0.841 (0.0001)	0.771 (0.0001)
Wet vs Dry formations	C_TSMRF	2018 – 1926	-0.036 (0.508)	-0.096 (0.859)
		2008 - 1926	-0.004 (0.356)	-0.059 (0.637)
		1998 - 1926	0.128 (0.113)	0.006 (0.346)
	TSMRF	2018 – 1926	-0.023 (0.484)	-0.023 (0.476)
		2008 - 1926	-0.023 (0.451)	-0.016 (0.426)
		1998 - 1926	0.008 (0.331)	-0.013 (0.410)
Wet vs Dry classes	C_TSMRF	2018 – 1926	-0.097 (0.996)	-0.099 (0.993)
		2008 - 1926	-0.112 (1)	-0.103 (0.997)
		1998 - 1926	-0.099 (0.999)	-0.113 (1)
	TSMRF	2018 – 1926	-0.097 (0.999)	-0.105 (0.993)
		2008 - 1926	-0.12 (0.999)	-0.121 (0.998)
		1998 - 1926	-0.118 (0.999)	-0.12 (0.997)

Distributions were more synchronous among eastern formations (TSMRF; 70% similarity excluding Alpine) than among western (43% similarity; Figure 4.4). The dissimilarity among western formations was largely driven by the Grasslands and Freshwater Wetlands distributions which were skewed to shorter times since fire (Figure 4.2). Time since the most recent fire in Alpine vegetation was not synchronous with other eastern formations (35.9% similarity; Figure 4.4), as 93% of the area burnt in the most recent fires were restricted to five years (2007 – 2008 and 2002 – 2004). This heavy influence of one or two large fire events was similar to the western arid and semi-arid formations (Figure 4.2).

At a local scale, TSMRF distributions in eastern classes were also skewed to shorter intervals than (Figure 4.5*a, b*; Figure A3.6) and were not synchronous with western classes (Table 4.1; Figure 4.3*c*; Figure A3.6) at the three time periods tested (2018: Figure 4.5*c, d*; 2008 and 1998: A3.1 – A3.4). Within a formation, C_TSMRF distributions of classes were more similar among eastern formations than among western in NSW and NPWS LMZs (Figure 4.6; Figure A3.6, A3.7). Distributions varied markedly among the western and widespread formations that contained eastern classes (excluding Saline Wetlands, Figure 4.5*c, d*; Figure 4.6; Figure A3.6, A3.7), driven by the skew to shorter times since fire within eastern vegetation.

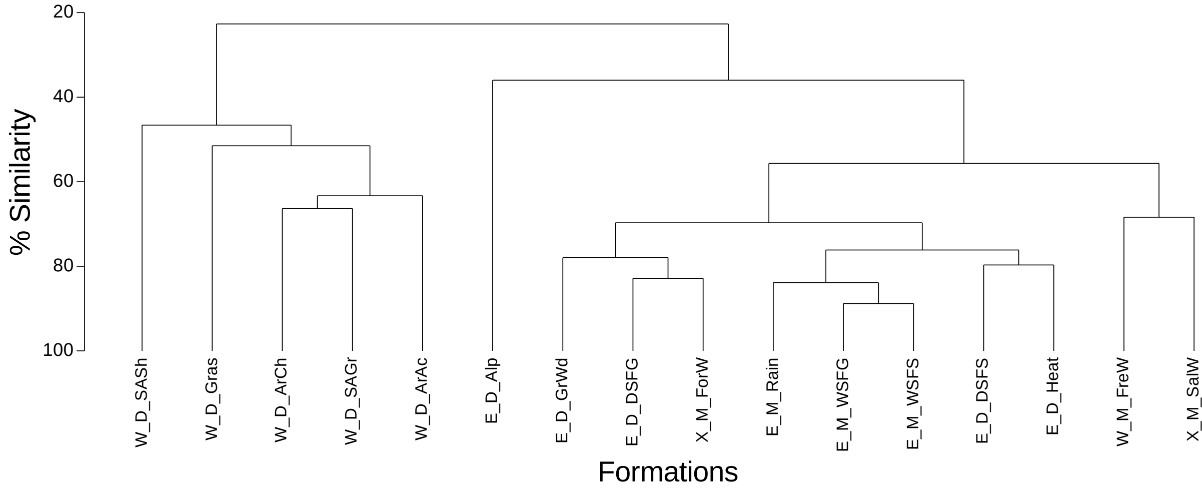


Figure 4.4 Dendrogram based on Bray-Curtis cluster analysis showing similarity among distributions of proportion of each vegetation formation recorded as burnt in each year of known fire history from 2018 to 1926 in New South Wales. E = eastern; W = western; X = widespread; D = dry; W = wet. See Table 2.1 for abbreviated name definitions

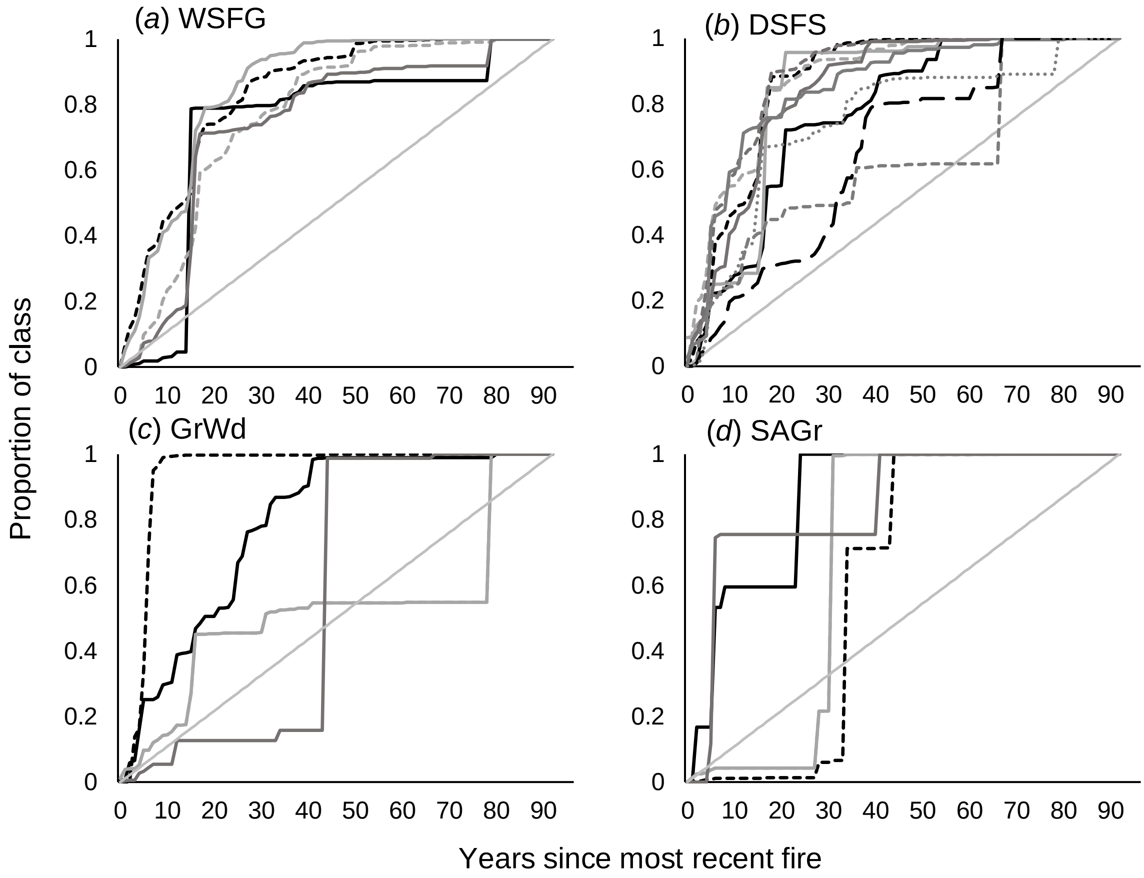


Figure 4.5 Cumulative proportion of most recent fires in each year of known fire history from 2018 for classes within (a) Wet Sclerophyll Forests (Grassy sub-formation; WSFG), (b) Dry Sclerophyll Forests (Shrubby/Grassy sub-formation; DSFS), (c) Grasslands (GrWd, and (d) Semi-arid Shrublands (Grassy sub-formation; SAGr). The grey diagonal lines represent an even distribution

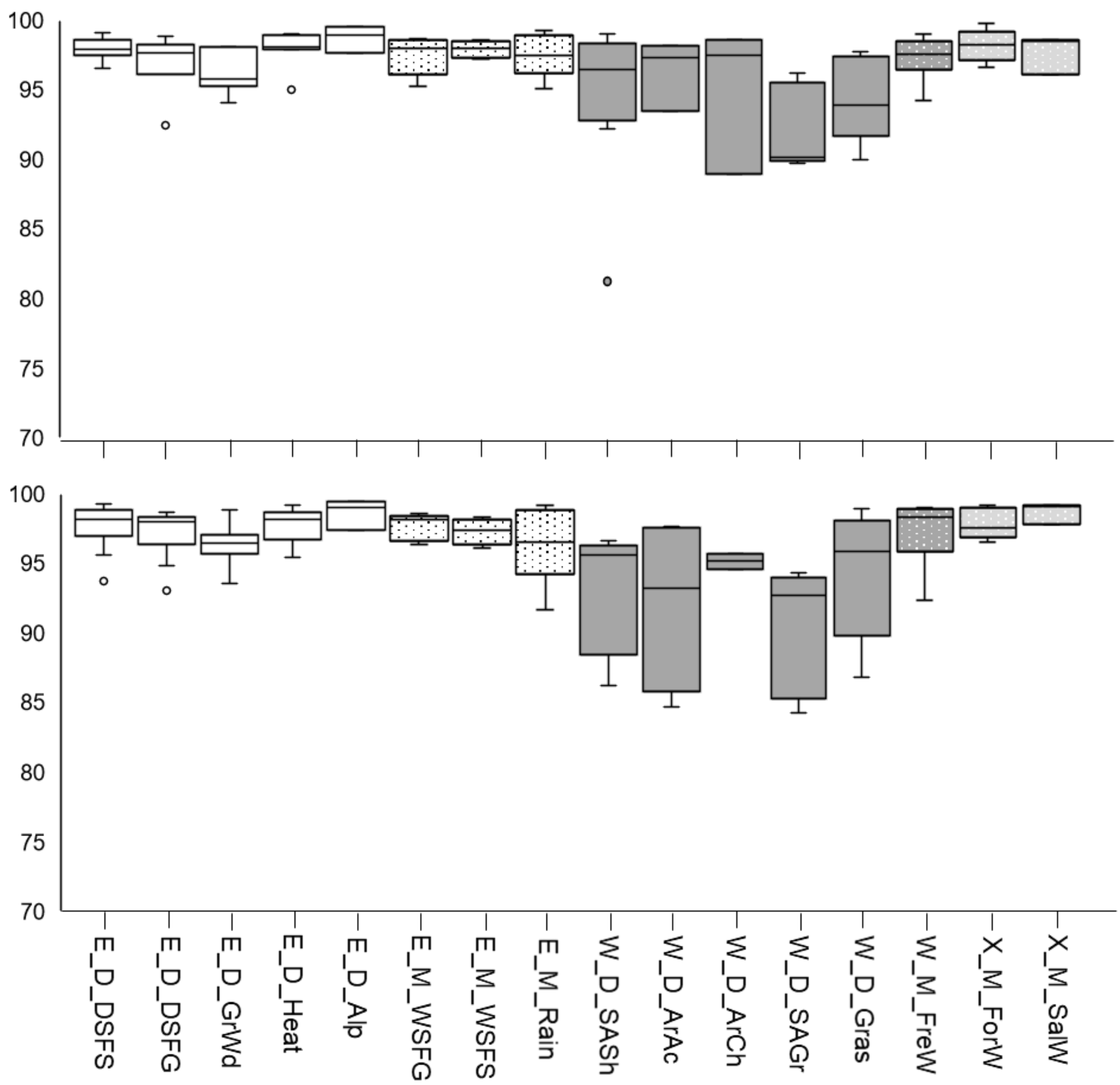


Figure 4.6 For each formation the median Bray Curtis similarity (%) of the cumulative proportion distributions of time since fire from 0 to 96 years since the most recent fire for each class when compared with the cumulative proportion distributions of their respective formation within (a) New South Wales and (b) the proportion of each vegetation type within NSW National Parks and Wildlife Service Estate Land Management Zones (NPWS LMZ). The horizontal middle line represents the median value, the shaded box represents the central 50% of data and the lines represent the lower and upper 25% of data. Circles designate outliers (points >1.5 times the interquartile range from the upper or lower quartile). E = eastern; W = western; X = widespread; D = dry; W = wet. See Table A3.1 for locations of classes

At an even finer scale, TSMRF distributions for formations were similar within a bioregion but not between bioregions (2-way crossed ANOSIM, bioregion: r = 0.22, P = 0.0001; formation: r = 0.047, P = 0.117). Of the 55 pair-wise comparisons among distributions between formations, 44 were similar and 11 were different (P = <0.05). Eight of these were between wet and dry formations (e.g., Dry sclerophyll Forest (Shrubby/Grassy) and Saline Wetlands: r = 0.247, P = 0.041), and three between formations occurring only within small patches in the bioregion (e.g., Freshwater Wetlands and Saline Wetlands: r = 0.358, P = 0.007). This also held within NPWS LMZ (2-way crossed ANOSIM, bioregion: r = 0.221, P = 0.0001; formation: r = -0.007, P = 0.551).

Distributions of time since fire for the proportion of each class in a bioregion also tended to group by location (Figure 4.7), with classes in the northern bioregions more similar to each other (73% similarity) than to the southern (51%) or central (68%) bioregions. There was more variation among the class distributions in the southern bioregions than the northern (Figure 4.7).

Contrary to my predictions, distributions were synchronous between wet and dry vegetation at a regional scale in NSW (Figure 4.3, Table 4.1) and were skewed to shorter times since fire (Figure 4.2). The C_TSMRF distribution of the one western wet formation was more similar to the eastern wet formations (99% similarity) (Figure 4.4). This held at a local scale, with the two western wet classes similar in distribution to the eastern wet classes (TSMRF; Figure A3.6; Table 4.1) and skewed to shorter times since fire (C_TSMRF; Figure A3.6).

At an even finer scale, distributions of time since fire were synchronous among wet and dry classes within a bioregion, but not between bioregions (2-way crossed ANOSIM, bioregion: r = 0.223, P = 0.0001; formation: r = 0.02, P = 0.134). This also held within

NPWS LMZ (2-way crossed ANOSIM, bioregion: r = 0.263, P = 0.0001; formation: r = -0.013, P = 0.222).

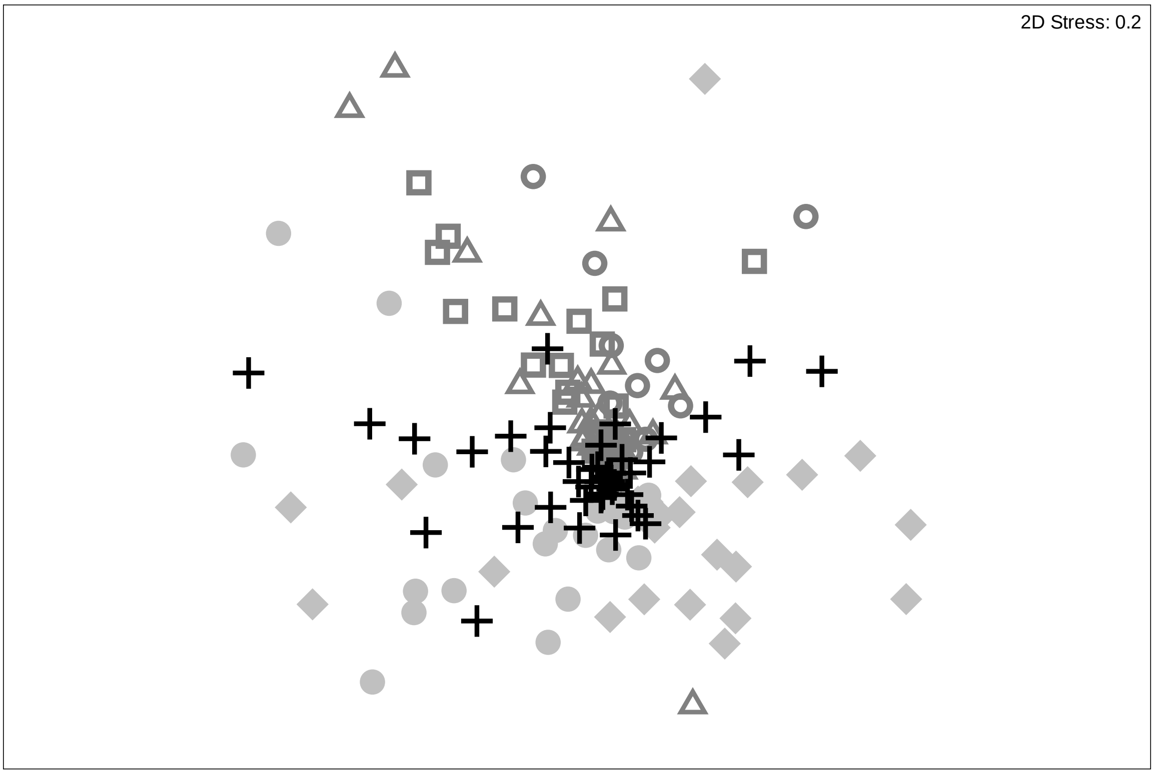


Figure 4.7 Non-metric multidimensional scaling ordination (fourth root transformed and Bray-Curtis similarity) of the proportion of each class within the six eastern most bioregions in NSW: New England Tableland (northern, dark grey open square); NSW North Coast (northern, dark grey open triangle); South East Queensland (northern, dark grey open circle) ;South East Corner (southern, light grey diamond); South Eastern Highlands (southern, light grey circle) and Sydney Basin (central, black cross)

4.5.2 Predictors of time since fire distributions

The strongest suite of environmental predictors of similarities among distributions of time since fire varied from three to five variables (Table 4.2). Within NSW as a whole, the strongest suite was found at four variables, after which any additional variables only slightly increased or decreased the correlation coefficient (0 – 0.2%). The proportion of the vegetation type with two fires recorded, annual mean temperature and rainfall, and proximity to parks or conservation areas were the most consistent predictors of similarity in time since fire distributions among formations in NSW at a regional and fine scale (Table 4.2). This varied slightly within the LMZ portion of each vegetation type, where the strongest suite was three variables for formations and five for classes. The proportion of the LMZ with two and three fires recorded, annual mean temperature and rainfall and proximity to non-wooded agriculture were the most consistent predictors (Table 4.2). Mean population and mean distance to roads/fire trials were not strong predictors of distributions of time since fire.

4.5.3 Areas managed for biodiversity

Within areas managed for biodiversity, distributions of time since the most recent fire generally followed the same trends as in NSW as a whole in 2018, 2008, and 1998; eastern vegetation types had distributions skewed to shorter times since fire (Figures A3.1, A3.2), and were not synchronous with those in western vegetation (Table 4.1; Figure A3.5). Wet and dry vegetation types had similar distributions of time since fire in the east (Table 4.1; Figures A3.1 - A3.4). This held for the three time periods tested (Figures A3.1 - A3.4). Unlike in NSW as a whole, within NPWS LMZ eastern wet classes were not synchronous with western wet classes (Table 4.1).

In 2018, ten of the 12 formations (80%) and 68 of the 80 classes (85%) with guidelines met the recommended targets of <35% of their area with a time since fire below the minimum intervals, and twelve formations (100%) and 76 classes (95%) met the target of <35% above the maximum intervals (Table 4.3). Only four formations (33%) and 25 classes (31%) met the target of >50% within the intervals (Table 4.3). The percentages of vegetation types were largely similar for each target in 2008 and 1998 (Table 4.3).

If the same intervals were assumed within NSW as a whole, the percentages of all vegetation types meeting the targets of <35% of their area with a time since fire below the minimum intervals and <35% above the maximum intervals were similar to NPWS LMZ. However, no formations would have met the target of >50% of their area between the minimum and maximum intervals in 2018, 2008 and 1998 and only between 4 and 14% of classes (Table 4.3).

Time since fire distributions (C_TSMRF) in eastern, western, wet, and dry formations differed overall to the most diverse distributions achievable under management guidelines (Guidelines; Table 4.4) and were skewed to shorter times since fire in eastern formations and longer in western in NPWS LMZ and non-NPWS (Figure 4.2). At a local scale, distributions differed overall to the Guidelines in NPWS LMZ but were similar in the non-NPWS portions (Table 4.4). Eastern classes were skewed to shorter times since fire than the Guidelines however were largely similar to each other (Table 4.4; Figure 4.8). Western classes were similar to the Guidelines overall (Table 4.4) however there was greater variability among the distributions (Figure 4.8). The distributions of wet classes varied from each other (Figure 4.8) and from the Guidelines (Table 4.4), however dry classes were more similar in distribution (Figure 4.8) and to the Guidelines within the non-NPWS portion but not within NPWS LMZs (Table 4.4).

Distributions differed between the non-NPWS portion and the NPWS LMZ portion for most formations (K-S *P*-values <0.001; Figure A3.8) with the exception of Dry Sclerophyll Forests (Grassy; eastern; K-S: D = 0.13978, P = 0.323), Wet Sclerophyll Forests (Shrubby; eastern; K-S: D = 0.12903, P = 0.421) and Forested Wetlands (widespread; K-S:

D = 0.13978, P = 0.324; Figure A3.8). Distributions in eastern formations were largely skewed to shorter times since fire within the non-NPWS portion than the NPWS-portion (with the exception of the Heathlands (eastern) formation; Figure 4.2; Figure A3.8). In western formations, distributions were skewed to shorter times since fire within NPWS LMZs than non-NPWS (Figure 4.2).

At a local scale, distributions in most dry classes were skewed to shorter times since fire in the NPWS LMZ portion than non-NPWS portion (Figure A3.8), except for classes within Arid Shrublands (chenopod) and Semi-arid Woodlands (Grassy) sub-formations. There were no clear patterns among wet formations, with some skewed to shorter times since fire in NPWS LMZ and others to longer, but there was little variation within a formation except within Wet sclerophyll Forests (Shrubby sub-formation; Figure 4.9).

Table 4.2. Predictors of the distributions of time since most recent fire

Combinations of up to five (*n*) environmental variables as predictors identified from BEST analysis of the distribution of time since fire in formations and classes in New South Wales (NSW) and for the proportion of each vegetation type within NSW National Parks and Wildlife Service Estate Land Management Zones (NPWS LMZ) (optimal suite shown in bold) and weighted Spearman correlation coefficient (*Pw*)

	NSW Formations		**NSW Classes**		**NPWS LMZ Formations**		**NPWS LMZ Classes**	
n	Predictor	*Pw*	Predictor	*Pw*	Predictor	*Pw*	Predictor	*Pw*
1	Temp	0.454	2 fires	0.335	Temp	0.421	2 fires	0.309
2	2 fires Temp	0.595	2 fires Park	0.424	2 fires Temp	0.530	2 fires Rain	0.348
3	2 fires Park Temp	0.598	2 fires Grazing AMR	0.460	2 fires, N-wood Temp	0.557	**2 fires** **3 fires** **Rain**	**0.374**
4	**2 fires** **Park** **Temp** **Rain**	**0.613**	**2 fires** **Grazing** **Park,** **Rain**	**0.468**	2 fires 3 fires N-wood Temp	0.567	2 fires 3 fires Grazing Rain	0.368
5	2 fires 3 fires Park Temp Rain	0.611	2 fires 3 fires Grazing Riparian Rain	0.466	**2 fires** **3 fires** **N-wood** **Temp** **Rain**	**0.584**	2 fires 3 fires Grazing Temp Rain	0.367

Temp: annual mean temperature; Rain: annual mean rainfall; Grazing: grazing native vegetation; N-wood: non-wooded agriculture; Park: parks/reserves/conservation areas; Riparian: riparian/water; 2 fires: % of vegetation with two fires recorded; 3 fires: % of vegetation with 3 fires recorded

Table 4.3. Number of vegetation types meeting fire interval guidelines for biodiversity conservation

For 2018, 2008 and 1998: the number (and percentage of total) of formations and classes with <35% of their area below; with >50% of their area within; and <35% of their area above the maximum ecologically recommended intervals for New South Wales (NSW) (Kenny *et al.* 2003; Office of Environment and Heritage 2013) for NSW as a whole, and the proportion of each vegetation type within NSW National Parks and Wildlife Service Estate Land Management Zones (NPWS LMZ)

Time	Scale	Number (% of total) of vegetation types below minimum intervals	Number (% of total) of vegetation types within intervals	Number (% of total) of vegetation types above maximum intervals
NSW				
2018	Formation	10 (83%)	0 (0%)	12 (100%)
	Class	77 (96%)	11 (14%)	78 (98%)
2008	Formation	12 (100%)	0 (0%)	12 (100%)
	Class	72 (94%)	4 (5%)	77 (100%)
1998	Formation	12 (100%)	0 (0%)	12 (100%)
	Class	77 (100%)	3 (4%)	77 (100%)
NPWS LMZ				
2018	Formation	10 (83%)	4 (33%)	12 (100%)
	Class	68 (85%)	25 (31%)	76 (95%)
2008	Formation	10 (83%)	3 (25%)	12 (100%)
	Class	66 (86%)	10 (13%)	77 (100%)
1998	Formation	12 (100%)	2 (17%)	12 (100%)
	Class	75 (97%)	4 (5%)	77 (100%)

Table 4.4. Comparisons of time since fire distributions among vegetation types in New South Wales with the most diverse distributions achievable under current guidelines

Results of analysis of similarity (ANOSIM) (R and *P* values) comparisons of the cumulative proportion distributions of the proportion of each vegetation type within NSW National Parks and Wildlife Service (NPWS) Estate Land Management Zones (LMZ) and the proportion of each vegetation formation not within NPWS Estate LMZ (non-NPWS) with the most diverse distributions achievable under management guidelines (Kenny *et al.* 2003)

Comparison	Time span	NPWS_LMZ R (*P*)	Non-NPWS R (*P*)
Formations	2018 – 1926	0.447 (0.0001)	0.313 (0.001)
Classes	2018 – 1926	0.342 (0.0009)	0.154 (0.074)
Eastern formations	2018 – 1926	0.663 (0.002)	0.548 (0.002)
Western formations	2018 – 1926	0.4 (0.008)	0.448 (0.008)
Eastern classes	2018 – 1926	0.689 (0.001)	0.381 (0.002)
Western classes	2018 – 1926	0.13 (0.134)	0.113 (0.139)
Dry formations	2018 – 1926	0.504 (0.003)	0.333 (0.001)
Wet formations	2018 – 1926	0.625 (0.003)	0.667 (0.003)
Dry classes	2018 – 1926	0.208 (0.048)	0.066 (0.290)
Wet classes	2018 – 1926	0.738 (0.001)	0.484 (0.009)

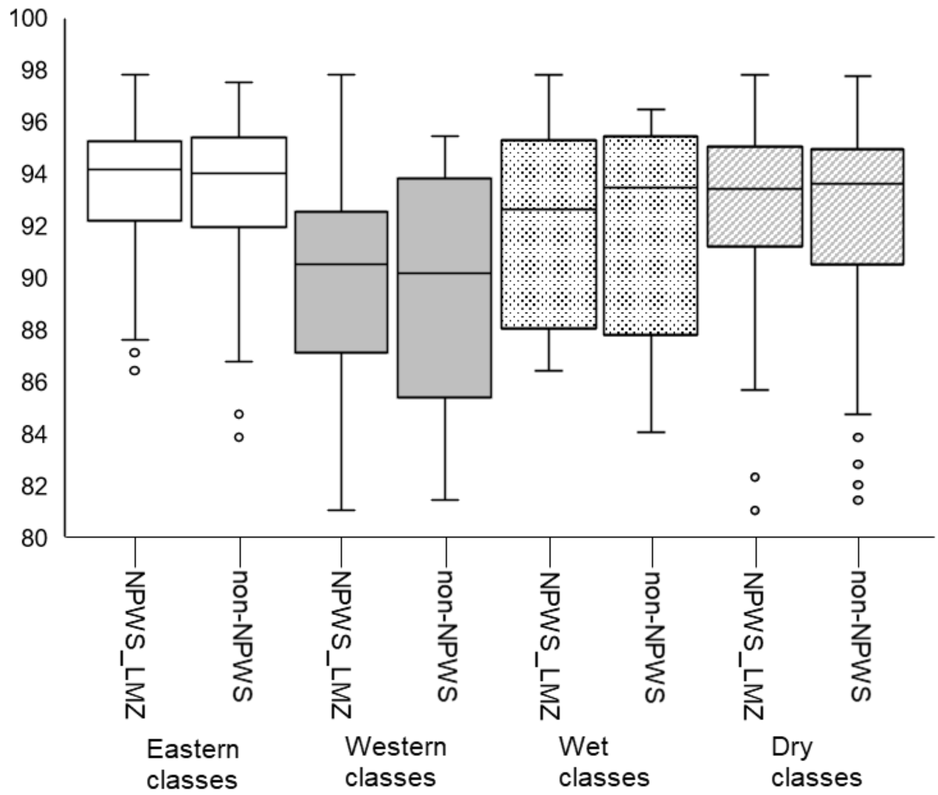


Figure 4.8 For the proportion of each vegetation type within NSW National Parks and Wildlife Service Estate Land Management Zones (NPWS LMZ) and the proportion of each vegetation formation not within NPWS Estate LMZ (non-NPWS) of each vegetation class: the median Bray Curtis similarity (%) of the cumulative proportion distributions of time since fire from 2018 to 1926 when compared with the most diverse distributions achievable under current management guidelines for their respective formation, grouped into all eastern (white), western (grey), wet (dark grey dots) and dry (light grey dots) classes. The horizontal middle line represents the median value, the shaded box represents the central 50% of data and the lines represent the lower and upper 25% of data. Circles designate outliers (points >1.5 times the interquartile range from the upper or lower quartile)

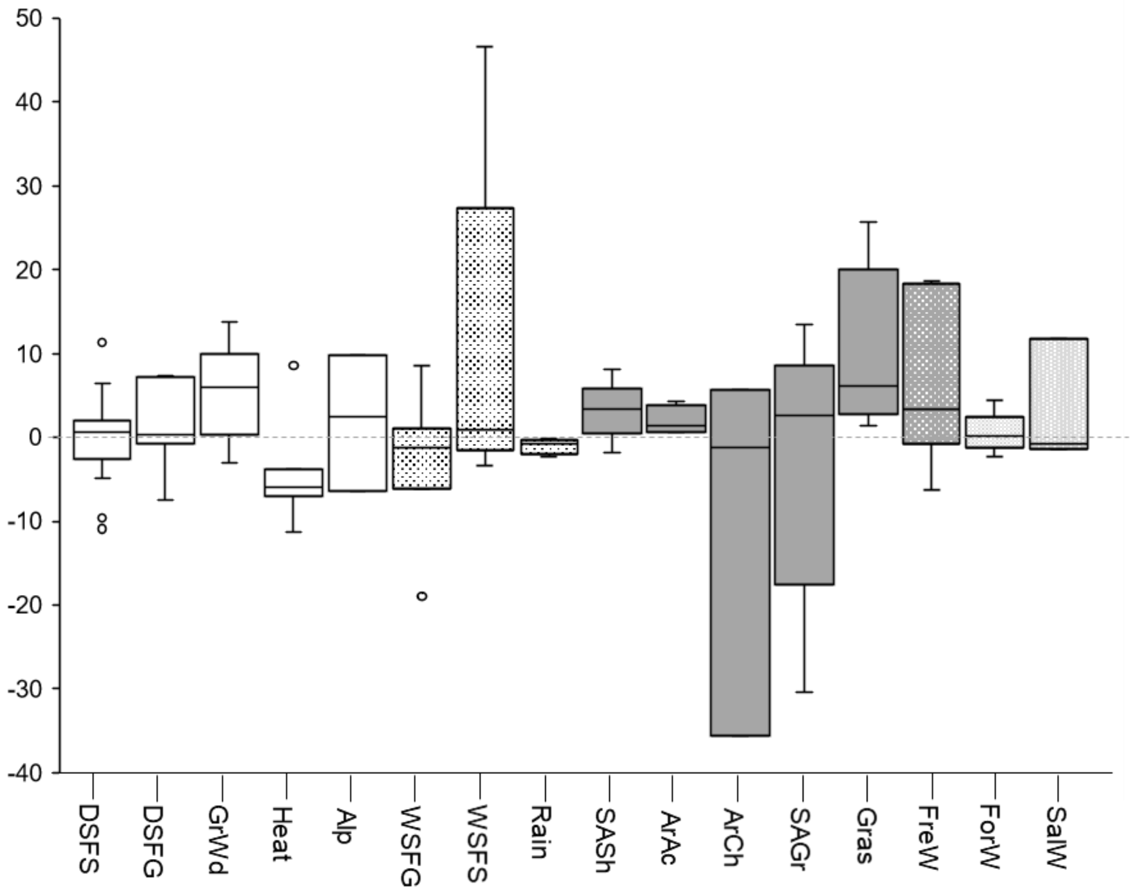


Figure 4.9 For each class within each eastern (white), western (dark grey), and widespread (light grey) formation (dots indicate wet formations), the difference in the cumulative proportion of area burnt per year between the proportion of each vegetation type within NSW National Parks and Wildlife Service (NPWS) Estate Land Management Zones (NPWS LMZ) and the proportion of each vegetation formation not within NPWS Estate LMZ (non-NPWS) for the 92 years between 2018 and 1926. Negative scores indicate distributions were skewed to shorter times since fire in non-NPWS than NPWS LMZ. The horizontal middle line represents the median value, the shaded box represents the central 50% of data and the lines represent the lower and upper 25% of data. Circles designate outliers (points >1.5 times the interquartile range from the upper or lower quartile). See Table A3.1 for locations of classes

4.6 Discussion

This examination of the NSW fire history shows that time since the most recent fire for large areas of NSW was skewed to shorter intervals through time and within areas managed for biodiversity conservation. As predicted, distributions varied by location, scale, and vegetation type however were similar between wet and dry vegetation, and vegetation types in close spatial proximity. Within areas managed for biodiversity, distributions were generally skewed to shorter times than the most diverse distributions achievable under management guidelines. Previous fire history, climate and land-use were stronger predictors of time since fire than other anthropogenic factors. The ability to address the aims of this chapter is compromised due to the errors in recorded fire history and gaps in the digitally stored fire history database identified in Chapter Three. However, the improvements in record keeping in the last two decades of the fire database (identified in Chapter 3.4.4) indicate that a subset of the last two decades of the database may provide more reliable data.

Longer fire intervals are typical of the less flammable arid and semi-arid vegetation, likely to be a consequence of lower productivity and fuel accumulation (Pausas and Bradstock 2007) with large fire events generally occurring after a build-up of biomass following intermittent rainfall events (Letnic and Dickman 2006). Sufficient biomass to carry a large fire can take from 10 – 20 to 30 – 50 years to build in semi-arid and arid wooded vegetation respectively (Bradstock and Cohn 2002; Hodgkinson 2002; van Etton and Burrows 2018) and time since fire distributions in NSW were consistent with the natural fire regimes for these vegetation types.

A skew to shorter times since fire in the mesic, eastern vegetation types of NSW would be expected as the availability of biomass to burn is positively associated with annual precipitation (Archibald *et al.* 2009; Bradstock 2010), and the highest rainfall in NSW occurs along the eastern coast. In coastal heathlands, sufficient fuel loads to carry a fire can build in as little as 18 months (Gill and Groves 1981; Bradstock *et al.* 1997) to 5 - 20 years (Bell *et al.* 1984; Enright *et al.* 2012), which can result in shorter fire intervals in the dry eastern vegetation types of NSW than the western vegetation. Within Dry Sclerophyll Forests fire can occur as frequently as every 2-5 years after a low intensity fire (Gill 1994; Morrison *et al.* 1996) but generally occur every 5 – 10 years (McArthur 1967). Intervals are slightly longer in Grassy Woodlands due to the lower rates of fuel accumulation and more open canopies (Walker 1981; Hobbs 2002).

The distributions of time since fire in NSW however may be impacted by the reliability of records within the fire databases. The population in western NSW is lower and sparser, and land use is largely agricultural. Fewer fires have been recorded in the arid and semi-arid vegetation, as fires occurring on private lands may not have been attended to by fire agencies and as such may not be recorded in the databases. There are numerous records of fires occurring in NSW prior to the 1970s not in the database, particularly within the arid and semi-arid vegetation of western NSW (Foley 1947; Table A2.1). The east coast region of NSW is the most densely populated, is where the highest proportion of Land Management Zones occur, and where the smallest proportion of area with no fire records occurs. Of the fires recorded in wet vegetation in NSW, only four percent have been recorded outside of an approximately 200 km strip along the east coast of NSW. The eastern coast has the largest wildfire-urban interface and as such fires were likely to be attended by fire agencies and recorded in the databases. Positive relationships have been demonstrated elsewhere between population density, fire occurrence (Keeley *et al.* 1999; Cardille *et al.* 2001; Syphard *et al.* 2007), and record keeping (Reddy and Davalos 2003; Guedes dos Santos *et al*. 2015). It was not possible to draw robust conclusions about how much of the variation in time since fire distributions among vegetation types in NSW was attributable to vegetation type or due to gaps in the fire history database.

It was predicted that time since fire distributions would differ between wet and dry vegetation, largely because wet vegetation has been shown to act as a natural barrier and limiting factor to fire spread (Kitzberger *et al.* 1997; Wood *et al*. 2011), and to burn less frequently and at a lower intensity than dry in many regions (Skinner 2003; Dwire and Kauffman 2003; Hamill and Bradstock 2009; van de Water and North 2010). Wet Sclerophyll Forests can accumulate large amounts of biomass however are less likely to burn than the dry forests due to the higher moisture levels, and stand killing fires generally occur once a century (McCarthy *et al.* 1999; Gill and Catling 2002). The highly fire sensitive rainforests of south-eastern Australia experience mean natural fire intervals of 300 years (Gill and Catling 2002).

Much of the vegetation on the east coast of NSW has experienced high levels of clearing and logging (Dillon *et al.* 2010; NSW Environmental Protection Agency 2018). Up to 78% of the sclerophyll forests in Australia have been logged at varying degrees of intensity (Keenan and Ryan 2004), and a greater proportion of wet vegetation (14%) in eastern NSW is designated for logging than dry (9%; Forestry Corporation of NSW 2021). Logging and clearing can alter the structure and composition of forests, leading to increased flammability in wet vegetation types (Pausas and Keeley 2014; Paritsis *et al.* 2015) and this provides one possible explanation for the skew to shorter times since fire in the wet vegetation in eastern NSW and the synchronicity of distributions with the dry vegetation. The synchronicity in the timing of fire events between wet and dry vegetation shown here have also been demonstrated elsewhere (e.g., North America; Olsen and Agee 2005; Charron and Johnson 2006).

However, the scale and accuracy of fire mapping could also mean unburnt patches are being recorded as burnt (Roy and Boschetti 2009; Padilla *et al.* 2015), leading to inflated area burnt recorded in the fire database. It is common for patches of vegetation within a fire perimeter to remain unburnt (Penman *et al.* 2007), particularly in complex landscapes such as much of eastern NSW, where fragments of less flammable, wet vegetation types are scattered within flammable, fire-adapted communities (Hamill and Bradstock 2009).

Increased fire activity in wet vegetation types may also be occurring due to drying of the vegetation through lower-than-average rainfall for many years from the early 2000s (BOM 2020*c*), increasing global temperatures and longer than usual fire weather seasons (Jolly *et al.* 2015), and long-term increases in the Forest Fire Danger Index (McArthur 1967; used to measure the influence of near-surface weather conditions on fire behaviour; Dowdy 2018). The skew to shorter times since fire through time, particularly in the eastern wet vegetation, was consistent with other studies showing fire frequency and annual area burned increasing in Australia (Dutta *et al*. 2016) and other fire-prone environments globally (Kasischke and Turestsky 2006; Littell *et al.* 2009; Miller *et al.* 2012; Brando *et al*. 2014).

Vegetation in NSW is categorised into formations by structural, physiognomic, and functional characteristics (Keith 2004) resulting in vegetation types that span large areas of varied topography and geology. Fire management for biodiversity conservation is implemented at the formation level (Kenny *et al.* 2003; Office of Environment and Heritage 2013). However, post-fire vegetation structure is influenced by differences between vegetation types and abiotic factors, and the degree to which habitat is impacted varies with landscape attributes (e.g., topographic variation; Bassett *et al.* 2015), fire history (Bradstock *et al.* 2005), habitat conditions, and climatic factors (Letnic *et al.* 2004).

Variations in fire regimes have been shown to be strongly associated with local topography, climate (Beaty and Taylor 2001; Hellberg *et al.* 2004; Flatley *et al.* 2011), soil and geological features (Fensham and Kirkpatrick 1992; Keith 2011) and it was expected that the distributions of time since fire would vary at a local scale from those at a regional scale.

The results found here suggest more factors than just vegetation type contribute to fire occurrence and local scale climatic and land use factors are strong predictors of distributions of time since fire. In contrast to other regions where proximity to high population and road densities have been found to positively influence the occurrence of fire (Sypahrd *et al.* 2007; Yang *et al.* 2007; Liu *et al.* 2012; Chas-Amil *et al*. 2013; Kolanek *et al.* 2021), previous fire history was the most consistent predictor of the distributions of time since fire in NSW. High fire frequency in previously burned landscapes have been demonstrated elsewhere (e.g., France: Mouillot *et al.* 2003; Spain: Diaz-Delgado *et al.* 2004; Vazquez and Moreno 2001). Given the strong influence of local scale factors on distributions of time since fire in NSW, intervals aimed at conserving biodiversity implemented at a formation level may be too broad to capture species responses to subtle variability in the habitat structure at a finer scale (e.g., Monamy and Fox 2000).

It was expected time since fire distributions within areas managed for biodiversity would be similar to the most diverse distributions achievable under management guidelines as in areas managed for biodiversity conservation the timing of fires can be manipulated for conservation outcomes. Despite most vegetation types meeting the minimum interval target within areas managed for biodiversity, distributions within NPWS LMZs were skewed to shorter times since fire. Frequent fire can negatively impact biodiversity as it can homogenise vegetation in the landscape, reducing the complexity, availability, and quality of habitat for fauna (Aponte *et al.* 2014; Croft *et al.* 2016).

Frequent fire can also reduce the proportion of mid- to older-age vegetation in the landscape, which has been found to be disproportionately important for the persistence of some species in different ecosystems (Geerts *et al.* 2012; Di Stefano *et al.* 2013; Kelly *et al.* 2015; Hale *et al.* 2016). As such, although vegetation in the landscape may meet the guideline intervals based on plant responses to fire, the landscape may not be suitable for the conservation of all fauna species, particularly those whose persistence depends on old growth vegetation (Kelly *et al.* 2015). However, due to the large areas of NSW with no fire records and a lack of historic records in the database, it is likely a greater proportion of vegetation has a time since the most recent fire above the maximum intervals which would affect the skew of time since fire distributions.

4.7 Conclusions

My analyses show that distributions of times since fire for much of NSW and areas managed for biodiversity conservation were skewed to shorter times but were synchronous between moist and dry vegetation types in eastern NSW. It was not able to be determined how much, if any of the synchronicity was due to inaccurate fire mapping. Time since fire distributions followed predicted trends at a regional scale but vary considerably at a local scale. However, distributions of time since fire were similar in close spatial proximity irrespective of the vegetation type. The variations in distributions of time since fire in NSW were related to local scale factors of previous fire history, location, and land-use. The results were limited by the reliability of fire records in the NSW fire history database, and it was unable to be determined how much of the variation in distributions were attributable to poor fire record keeping.

Fire management for biodiversity outcomes in NSW are currently based on key plant species fire responses at broad vegetation groups. Given the strong influence of local scale factors on time since fire distributions, fire management for biodiversity conservation may need to focus on a finer scale than is currently implemented.

Chapter 5 Similar fire history does not equate to similar fauna habitat in structurally similar vegetation

5.1 Abstract

In this study I investigate the impacts of vegetation type, fire history, and environmental factors on habitat attributes. Although similar in structure and physiognomy, it was the floristic and fine-scale structural differences that were the greatest drivers of variation in habitat in the three vegetation types I examined. Characteristics of the most recent fire and the interval to the next fire did not have as strong an effect on habitat as vegetation type. The fire type (wild versus prescribed) was one of the best predictors for variation in the landscape for some habitat types. There was a weaker, but significant effect on fauna habitat of time unburnt prior to a fire and whether the fire is wild or prescribed. However, these effects of fire varied among vegetation types. My findings demonstrate that key habitat types important for the persistence of fauna did not have a uniform response among vegetation types at a local scale. Fire management practices designed for managing plant species survival are based on predictable plant responses to fire at a formation-scale, however these results demonstrate that the response of key fauna habitat attributes is not predictable at this scale and fire management may need to be directed at a finer-scale than that at which they are currently managed.

5.2 Introduction

Fire plays a key role in determining fauna occurrence, distribution, and abundance across fire-prone landscapes (Hutto 2008; Lindenmayer *et al.* 2008*c*). Fire has direct effects on animals, including mortality due to heat or smoke or increased predation (Russell *et al.* 2003), or indirect effects via impacts on habitat or resources (Fox 1982). Fire can alter the structure of ecological communities by changing the spatial patterns of vegetation and the composition of plant species (Morrison *et al.* 1995; Bond and van Wilgen 1996), which can influence the suitability of habitat for fauna (Catling 1991; Fox 1982).

Ecological fire management aims to conserve biodiversity, often by maintaining patches of differing fire histories to promote species diversity within a landscape (Bradstock *et al*. 2005; Parr and Andersen 2006; Spies *et al*. 2012). One way of estimating appropriate fire regimes is based on functional life-history traits of species relating to responses to fire, using a framework of recommended minimum and maximum fire intervals required for a particular vegetation type to maintain plant diversity (Noble and Slatyer 1980; Kenny *et al.* 2003). However, these programs are generally based on managing vegetation and rarely make reference to considerations for fauna (Clarke 2008; MacHunter *et al*. 2009). The broad- blanket statement approaches of these strategies are limited by a lack of detailed knowledge of appropriate fire regimes for most fauna species (Bradstock and Cohn 2002; Clarke 2008). Therefore, broadly categorised land cover types will not always reflect the amount of suitable habitat for particular animal species.

The physiognomy and structural attributes of vegetation are critical determinants of which fauna occupy the landscape as they provide the habitat on which animals depend directly or indirectly for breeding, shelter, and food (MacArthur and MacArthur 1961; Brawn *et al.* 2001; Fisher 2001; Williams *et al.* 2002). At a fine scale, the availability of key habitat attributes such as hollows in trees and logs (Gibbons and Lindenmayer 2002) and ground, shrub, and canopy layers of the vegetation (MacArthur and MacArthur 1961; Major *et al.* 2001; Fischer *et al.* 2005; Debus *et al.* 2006) will determine how suitable a site is for individuals. Plant species composition can also influence the distribution of fauna directly and indirectly by influencing the abundance and types of food resources (Rotenberry 1985; Cueto and de Casenave 2000; Jayapal *et al.* 2009). Variations in climatic and environmental conditions, vegetation type (Keeley *et al.* 2005), and the fire regime all interact to cause fires to vary spatially and temporally in the landscape which influences the availability of habitat and resources (Smit *et al.* 2013).

Habitat suitability has been linked to time since fire in many ecosystems (Fox 1982; Kelly *et al.* 2011; Watson *et al.* 2012) however, fauna have been shown to respond to the post-fire changes in vegetation structure and resources rather than to time since fire *per se* (Monamy and Fox 2000, 2010; Fox *et al.* 2003). Variations in environmental factors such as topography, soil characteristics and climatic conditions (Gilbert and Lechowicz 2004; Shryock *et al.* 2015; Romme *et al.* 2016) can influence vegetation structure and habitat suitability. Topographic features can have indirect effects on habitat through their effects on solar insolation, soil moisture, vegetation composition, and fire behaviour (Dwyer and Merriam 1981; Collins *et al.* 2012; Bassett *et al.* 2015). Climatic conditions, particularly rainfall, are key drivers of vegetation recovery and fauna population dynamics after fire (Fisher and Owens 2000; Meserve *et al.* 2011; Plasvic 2014).

Habitat suitability can be altered by elements of the fire regime such as frequency, inter-fire interval, intensity, and season (Gill and Allan 2008; Greenberg *et al.* 2013). For example, frequent fire and inappropriate inter-fire intervals can simplify the vegetation structure and reduce the availability and quality of habitat resources (Weber and Flannigan 1997; Collins *et al.* 2012; Haslem *et al.* 2012). Fire severity can indirectly affect fauna via changes in habitat structure (Christensen *et al*. 1981; Smucker *et al.* 2005), homogeneity of habitat, or availability of refuges (Leonard *et al.* 2014).

Environmental factors can also influence elements of the fire regime. Fire tends to be more frequent in area of high productivity associated with increased moisture (Pausas and Bradstock 2007; Krawchuk and Moritz 2011), and the climatic conditions preceding fire can influence the fire return time (Keeley 2004; Archibald *et al.* 2010; Gibson *et al.* 2015). The severity of a fire will vary spatially in the landscape, due to variations in fire behaviour led in part, by variations in environmental gradients such as topography, as well as vegetation, and fire history (Hammill and Bradstock 2006; Schoennagel *et al.* 2008; Holden and Jolly 2011; Leonard *et al.* 2014).

The post-fire recovery of vegetation and habitat will also be influenced by the legacies of previous fires (Catling 1991; Gill and Catling 2002). The between fire interval and interval variability can influence plant species composition and reproduction (Morrison *et al.* 1995; Taylor *et al.* 1998), fauna species composition (Andersen *et al.* 2005; Smith *et al*. 2013), and habitat availability (Weber and Flannigan 1997; Haslem *et al.* 2012). Previous fires will vary in size and timing and, when overlain by later fires, create a complex pattern of patches of differing fire history and vegetation structure in the landscape (Avitable *et al.* 2013). Vegetation change resulting from historic fire regimes may differ depending on the spatial scale (Palmquist *et al.* 2014) and environmental context (Smith *et al.* 2013). As such, fire management for biodiversity conservation implemented at a landscape or vegetation type scale may be too broad to capture local differences in habitat due to local-scale variation in floristic composition, environmental factors, and disturbance history. Understanding how vegetation responds to fire regimes at different scales and in different vegetation types is key to managing for biodiversity conservation.

The overall aim of this study was to investigate the impacts of fire history, vegetation type, and environmental factors on habitat attributes. Specifically, I aimed to test the extent to which attributes of fauna habitat varied: (*i*) among vegetation types which are classified as structurally similar, with similar recent fire history but with differences in plant species composition; (*ii*) among areas of the same vegetation type, burnt at the same time, but with a different interval to the previous fire; and (*iii*) within and among vegetation types in relation to local environmental factors, wild versus prescribed fire, and proximity to each other.

5.3 Methods

5.3.1 Study area

The study area encompassed the Dry Sclerophyll Forests (Shrubby sub-formation) (DSFS; Keith 2004) vegetation in New South Wales (NSW), south-eastern Australia. DSFS covers 4.87 million hectares (ha) of eastern NSW and extends ~850 km from north to south and ~450 km east to west, commencing on the western side of the Great Dividing Range and extending east to the coast. Vegetation is classified as DSFS based on structural and physiognomic features (Keith 2004) and is characterised by a canopy of low scleromorphic trees, typically eucalypts, a scleromorphic shrub layer, and a sparse ground layer (Keith 2011). DSFS occurs on low-nutrient soils where mean annual rainfall ranges from 600 – 1000 mm but increases to 1000 – 1500 mm along the eastern coastal areas (Australian Bureau of Meteorology 2020).

Dry Sclerophyll Forests (Shrubby sub-formation) is further classified in to 14 vegetation classes which differ based on dominant canopy species, understorey floristics, topography, and soils (Keith 2004; Table 2.7). For this study I selected three classes

(Western Slopes Dry Sclerophyll Forests (DSF), Sydney Hinterlands DSF and Southern Tablelands DSF) (Figure 2.12; Table 2.7). The three classes were chosen as together, they span the latitudinal range of NSW but converge at a central location at the north-western edge of the Sydney basin (Figure 2.12).

For this study I only used DSFS that was within areas termed Land Management Zones (LMZs) (Office of Environment and Heritage 2013), within NSW National Parks and Wildlife Service (NPWS) Estate National Parks, Nature Reserves, State Conservation Areas or Regional Parks (Figure 2.13; Table SITES). In LMZs, asset protection is not the primary objective, and a key use of fire is to promote ecological outcomes such as biodiversity conservation. Guidelines for fire management of vegetation formations within NPWS Estate LMZs aim to ensure that each vegetation formation has a range of fire intervals aimed at minimising the loss of vascular plants and threatened fauna (Kenny *et al*. 2003). These guidelines identify for each formation/sub-formation: a minimum interval, the shortest inter-fire interval to avoid localised decline or loss of species due to too frequent fire (seven years for DSFS); and a maximum interval, a predicted time since fire beyond which plant species may be lost due to senescence of plants and stored seed (30 years for DSFS). These guidelines are based on knowledge of flora responses to fire and not fauna responses.

The fire history of NSW is stored within four digital datasets, three managed by the NSW Rural Fire Service (NSW RFS) and one by the NSW Office of Environment and Heritage (OEH; now Department of Planning, Industry and Environment). I determined the fire history of DSFS using the database created by merging these four datasets and removing all replicate records and non-fire records (see Chapter 2.2 and 2.3 for full details).

For my study I used GIS layers of this fire history database, the vegetation formations of NSW (version 3.03, Keith and Simpson 2010) and a GIS LMZ layer to define the boundaries of DSFS within NPWS Estate LMZs.

5.3.2 Site selection

The digital fire history data were used to select fifty-four sites, 18 sites in each vegetation class (Table 2.8; Figure 2.13). The 18 sites for each class were selected to span most of the north-south and east-west extent of each class (Figure 2.14) Sites were selected with the most recent fire as close as possible to six years before my sampling, but availability of sites resulted in between four and eleven years between the most recent fire and sampling (30 burned in 2013; Table 5.1). Fifty-one of the sites had more than one fire prior to 2013 recorded in the fire database. Three sites had only one fire, the most recent fire, recorded but were assumed to have greater than 30 years since the fire previous to that due to the quality of fire records for the area (Table 5.1).

For each class I selected six sites within each of three inter-fire interval groups (hereafter ‘interval groups’): between 1 and <7 years (‘below recommended intervals’ - less than the minimum recommended interval of 7 years for DSFS (Grassy/Shrubby); Kenny *et al.* 2003; Figure 2.14); between 9 and 29 years (within recommended intervals of 7 and <30 years; Figure 2.15); and between 31 and 78 years (‘above recommended intervals’ - longer than the maximum recommended interval of 30 years; Kenny *et al.* 2003; Figure 2.16). The six replicate sites in each class were selected to span as much of the inter-fire interval as possible (Figures 2.14 – 2.16).

The minimum distance between sites within a fire interval category for the same vegetation class was 10 km, with the majority separated by >60 km, and up to 450 km

(Figures 2.14 – 2.16). The minimum distance between sites within a fire interval but in different vegetation classes was 400 m (Figures 2.14 – 2.16).

5.3.3 Site layout

Within each site, two parallel 100 m × 10 m transects were laid out separated by 30 m, and both at least 50 m from the nearest road or trail. The two transects were positioned at a distance of 30 m apart. Four 10 m × 10 m quadrats were spaced 20 m apart along each transect (Figure 2.10) and two 2.5 m × 2.5 m sub-plots were placed in two opposite corners of each 10 m × 10 m quadrat (Figure 2.11).

Table 5.1. List of study sites

For each site: vegetation class, name of National Parks and Wildlife Service Estate, years between sampling and the most recent fire (TSF), recommended interval range in years (Range), year of most recent fire (Fire 1), year of previous recorded fire (Fire 2), number of years between Fire 1 and Fire 2 (Interval), and the date sampling occurred (Date). For Fire 1, W = wildfire and all other fires were prescribed

Site	Vegetation Class	NPWS Estate	TSF	Range	Fire 1	Fire 2	Interval	Date
JW001	Western Slopes	Durridgere State Conservation Area	6	0-6	2013	2010	3	11/09/2019
JW002	Western Slopes	Goulburn River National Park	6	0-6	2013	2011	2	02/07/2019
JW003	Western Slopes	Goobang National Park	6	0-6	2013	2008	5	06/08/2019
JW004	Western Slopes	Goonoo State Conservation Area	6	0-6	2013	2011	2	08/08/2019
JW005	Western Slopes	Timallallie National Park	6	0-6	2013 (W)	2007	6	16/08/2019
JW006	Western Slopes	Pilliga East State Conservation Area	9	0-6	2010	2009	1	19/08/2019
JW007	Western Slopes	Wollemi National Park	6	7 -29	2013	1985	28	22/07/2019
JW008	Western Slopes	Timallallie National Park	6	7 -29	2013 (W)	2009	9	18/08/2019
JW009	Western Slopes	Binnaway Nature Reserve	6	7 -29	2013	2002	11	14/08/2019
JW010	Western Slopes	Pilliga East State Conservation Area	6	7 -29	2013	1997	16	20/08/2019
JW011	Western Slopes	Goobang National Park	9	7 -29	2010	1983	28	07/08/2019
JW012	Western Slopes	Nangar National Park	8	7 -29	2011	1998	12	16/09/2019
JW013	Western Slopes	Wollemi National Park	6	30+	2013	1982	31	13/09/2019
JW014	Western Slopes	Goobang National Park	8	30+	2011	1979	32	08/08/2019
JW015	Western Slopes	Warrumbungle National Park	6	30+	2013 (W)	1935	78	15/08/2019
JW016	Western Slopes	Pilliga East State Conservation Area	6	30+	2013	1951	62	21/08/2019
JW017	Western Slopes	Bullala National Park	7	30+	2012			22/08/2019

Site	Vegetation Class	NPWS Estate	TSF	Range	Fire 1	Fire 2	Interval	Date
JW018	Western Slopes	Weetalibah Nature Reserve	5	30+	2015	1965	50	13/08/2019
JW019	Sydney Hinterland	Ku-ring-gai Chase National Park	11	0-6	2009	2003	6	07/01/2020
JW020	Sydney Hinterland	Goulburn River National Park	6	0-6	2013	2011	2	01/07/2019
JW021	Sydney Hinterland	Berowra Valley National Park	8	0-6	2012	2011	1	09/01/2020
JW022	Sydney Hinterland	Blue Mountains National Park	7	0-6	2013 (W)	2010	3	21/02/2020
JW023	Sydney Hinterland	Wollemi National Park	6	0-6	2013	2011	2	09/07/2019
JW024	Sydney Hinterland	Yengo National Park	9	0-6	2010	2009	1	09/09/2019
JW025	Sydney Hinterland	Dharawal State Conservation Area	6	7 -29	2014	2001	13	20/02/2020
JW026	Sydney Hinterland	Yellowmundee Regional Park	6	7 -29	2013 (W)	2011	12	10/07/2019
JW027	Sydney Hinterland	Yengo National Park	8	7 -29	2011 (W)	2002	9	10/09/2019
JW028	Sydney Hinterland	Upper Nepean State Conservation Area	6	7 -29	2013	1984	29	12/12/2019
JW029	Sydney Hinterland	Ku-ring-gai Chase National Park	5	7 -29	2015	1990	25	08/01/2020
JW030	Sydney Hinterland	Morton National Park	6	7 -29	2013	2000	13	15/10/2019
JW031	Sydney Hinterland	Wollemi National Park	7	30+	2012	1980	32	12/11/2019
JW032	Sydney Hinterland	Bargo River State Conservation Area	6	30+	2013	1968	45	28/11/2019
JW033	Sydney Hinterland	Ku-ring-gai Chase National Park	10	30+	2010	1979	31	06/01/2020
JW034	Sydney Hinterland	Blue Mountains National Park	9	30+	2011			11/07/2019
JW035	Sydney Hinterland	Cattai National Park	7	30+	2014			17/02/2021
JW036	Sydney Hinterland	Morton National Park	6	30+	2013	1982	31	16/10/2019
JW037	Southern Tablelands	Winburndale Nature Reserve	6	0-6	2013	2008	5	17/07/2019
JW038	Southern Tablelands	Cuumbeun Nature Reserve	6	0-6	2015	2013	2	21/01/2021
JW039	Southern Tablelands	Kosciuszko National Park	8	0-6	2013	2009	4	19/01/2021

Site	Vegetation Class	NPWS Estate	TSF	Range	Fire 1	Fire 2	Interval	Date
JW040	Southern Tablelands	Abercrombie River National Park	7	0-6	2012	2010	2	12/10/2019
JW041	Southern Tablelands	Kosciuszko National Park	11	0-6	2010	2007	3	26/01/2021
JW042	Southern Tablelands	Wollemi National Park	10	0-6	2009	2006	3	21/07/2019
JW043	Southern Tablelands	Winburndale Nature Reserve	5	7 -29	2014 (W)	2002	12	19/07/2019
JW044	Southern Tablelands	Dangelong Nature Reserve	8	7 -29	2013 (W)	1987	26	22/01/2021
JW045	Southern Tablelands	Nangar National Park	11	7 -29	2010	1986	24	15/02/2021
JW046	Southern Tablelands	Brindabella National Park	8	7 -29	2013	2002	11	20/01/2021
JW047	Southern Tablelands	Abercrombie River National Park	6	7 -29	2013 (W)	1998	15	11/10/2019
JW048	Southern Tablelands	Coolumbooka Nature Reserve	8	7 -29	2013	1989	24	25/01/2021
JW049	Southern Tablelands	Woomargama National Park	6	30+	2015	1984	31	18/01/2021
JW050	Southern Tablelands	Wollemi National Park	9	30+	2010	1979	31	20/07/2019
JW051	Southern Tablelands	Winburndale Nature Reserve	6	30+	2013	1971	42	18/07/2019
JW052	Southern Tablelands	Weddin Mountains National Park	6	30+	2013	1974	39	09/10/2019
JW053	Southern Tablelands	Morton National Park	6	30+	2013	1964	49	14/10/2019
JW054	Southern Tablelands	Merriangaah Nature Reserve	6	30+	2013	1939	74	23/01/2021

5.3.4 Data collection

Data collection was undertaken between July 2019 and January 2021. Here I describe the general methods of data collection for habitat attributes made at each site. A more in-depth description of the vegetation and habitat characteristics measured at each site can be found in Chapter 2 (Table 2.9; see Sections 2.4.2 – 2.4.4).

In each 10 m × 10 m quadrat I recorded the characteristics of: all trees (stem ≥ 15 cm diameter at breast height (DBH) at 1.3 m above the ground and ≥2 m tall); logs (diameter ≥10 cm); stumps (height ≥30 cm and <2 m tall, diameter ≥ 10 cm at 30 cm height); vegetation structure; leaf litter; and canopy structure and solar radiation transmittance.

For each tree I measured DBH at 1.3 m above ground for each stem, tree height, condition (live or dead), presence of scorching, number, and size of hollows (estimated if out of reach), presence of mistletoe or decorticating bark, presence of epicormic growth, and presence of basal growth resprouts > 1.3 m tall. For stumps I measured the diameter at 30 cm above ground and recorded the presence of scorching or evidence of being cut down. For each log I measured the total length, length of scorching, the diameter at each end and the mid-point of the log, the height above ground, and the number and size of any hollows in the log.

Understorey vegetation density was measured at four heights (0 – 20 cm, 20 – 50 cm, 50 – 100 cm and 100 – 150 cm) above the ground by observing a 50 cm × 20 cm chequered coverboard from a distance of 2 m and 5 m in four directions.

I measured leaf litter depth and collected a leaf litter sample from an area of 50 cm × 10 cm down to soil level at the centre of each quadrat. Each leaf litter sample was weighed in the field using a spring balance to the nearest gram. The leaf litter was dried in an oven for at least 72 hours at 80^{o} C to constant weight (i.e., until there was a change of <0.15g for two consecutive days).

A hemispherical photograph was taken at the centre of each quadrat. Canopy structure and solar radiation transmittance were calculated from hemispherical images using Gap Light Analyzer software (version 2.0; Frazer *et al.* 1999). For consistency, all images were processed with a pixel intensity threshold of 128.

In each 2.5 m × 2.5 m subplot I measured the heights of the understorey vegetation in three strata groups (near surface: live foliage 0 cm – 49 cm; elevated: live foliage 50 cm – 99 cm; intermediate: live foliage 1 m – 2 m). I also measured the characteristics of the coarse woody debris (CWD) and ground cover. CWD was defined as dead branches on the ground with a diameter ≥5 cm and < 10 cm. For each piece of CWD I measured diameter in three places (each end and a mid-point), length of all coarse woody debris, presence of scorching, and the maximum height above the ground.

The proportional cover of the ground by living plants, leaf litter (including sticks <2 cm diameter), bare ground, fine woody debris (sticks >2 cm and <5 cm diameter), CWD, logs, rocks and soil crusts was measured in one corner of each sub-plot). All habitat attributes and variables derived from the attributes that were used in the analyses are listed in Table 2.9.

5.3.5 Environmental and fire history attributes

Environmental, climatic and fire history predictors were calculated for each site (Table 2.10). Climatic variables were obtained from the nearest Bureau of Meteorology weather stations to each site. Slope, aspect, and soil types were calculated in ArcMap (ESRI 2013). Aspect was sine and cosine transformed to obtain a continuous gradient (northness and eastness). Time since the most recent fire, number of known fires, fire type (wild or prescribed) and the number of years between the most recent fire and the fire before that were determined based on information in the digital fire database.

5.3.6 Grouping habitat variables into habitat types

Given the large number of habitat measurements made, and the likelihood of correlations among variables, I grouped variables to be analysed to produce a smaller number of derived variables (hereafter termed ‘habitat types’). Individual habitat variables were grouped based on type of variable and published responses of fauna to habitat at different scales (Table 5.2).

5.3.7 Statistical analysis

5.3.7.1 Underlying differences among vegetation types and inter-fire interval groups

Given the differences in location, canopy dominants and understorey floristics among vegetation types, there may be inherent differences among the sites that could affect analyses of habitat structure. It was not possible to exactly match the fire history of sites selected in each of the vegetation types and for each of the interval groups. Therefore, prior to further analyses I examined underlying differences in fire history (fire type (wild or prescribed), years since the most recent fire, and inter-fire interval) among vegetation types and interval groups. I also compared environmental attributes (slope, aspect, mean annual rainfall, total rainfall in the 24 months post fire (total rain), and mean annual temperature) among vegetation types and interval groups. These results guided the selection of predictor variables in subsequent analyses.

5.3.7.2 Derived habitat types

I used Principal Component Analysis (PCA) in SPSS version 25 (SPSS: IMB Corp. 2017) to derive a smaller number of biologically meaningful habitat types from the habitat variables at a site scale and at quadrat scale (Table 5.2). Data were $\log_{10}$ transformed prior to analyses when required.

The assumptions for PCA were considered to be met if at least one correlation coefficient was >0.3, the overall Kaiser-Meyer-Olkin measure was >0.7, and Bartlett's test of sphericity was statistically significant ($P < 0.05$). Principal components with eigenvalues >1 were considered for retention.

5.3.7.3 Predictors of differences in habitat

To test for variability in the response of vegetation to fire regimes at different scales and in different vegetation types I analysed data at the site scale and at the finer scale of quadrat. I used Generalised Linear Modelling (GLMs) using the 'glm' function in R (R Core Team 2021) to examine the extent to which habitat at a site level was predicted by vegetation type, fire history, and environmental factors. Predictors were selected from among the variables vegetation type, interval group and the environmental and fire attributes listed in Table 2.10 and interactions among these. Response variables were the principal components and eight individual habitat variables that were not well-incorporated into the principal components. Some of the response variables may influence the amount or quality of habitat (e.g., the number of tree stems) and as such were used as predictor variables in some of the models. As fire management is prescribed at the formation rather than the class level, models were also fitted excluding vegetation type to investigate the influence of the level that vegetation is considered.

Generalised Linear Mixed Models (GLMMs) in R (R Core Team 2021) using the ‘lmer’ function from the ‘lme4’ package (Bates *et al.* 2015) were used to assess the extent to which quadrat-level habitat principal components were predicted by vegetation type, fire history and environment. The ‘lmerTest’ package (Kuznetsova *et al.* 2017) was used to derive the degrees of freedom and p-values for mixed models using transect and site as random effects. Predictors were selected from among the variables vegetation type, interval group, and the environmental and fire variables listed in Table 2.10. The *Poisson* family was used for models of habitat variables that were count data, and *binomial* for variables that were presence/absence. The conditional and marginal R^2 values were calculated using the ‘r.squaredGLMM’ function from the ‘MuMIn’ package (Barton 2020).

For both GLM and GLMM, model selection was based on Akaike Information Criterion (AIC) values. The preferred model was the one with significant predictor variable(s) and the lowest AIC value. Any models with significant predictor variables and with an AIC value not more than two points higher than the preferred model were also reported.

5.3.7.4 Proximal similarity among sites

I used spatial autocorrelation to test if habitat variables and principal components at sites had a geographically driven pattern irrespective of vegetation types and fire history. Spatial autocorrelation uses a matrix of geographical distances between sites to determine a correlation among values of an attribute weighted by their locational proximities (Diniz-Filho *et al.* 2003). A positive correlation represents similarity in values for geographically nearby sites, and a negative correlation for contrasting values (Legendre 1993).

Spatial autocorrelation was analysed using the Moran’s I Autocorrelation Index (‘Moran.I’ in the ‘ape’ package (Paradis and Schliep 2019) in R (R Core Team 2021)).

Table 5.2. Habitat types used by fauna groups

Habitat types with the relevance to particular fauna groups and literature sources providing evidence for grouping.

Habitat type	Fauna habits/behaviour/use	References
Ground Cover (0-50 cm)	Litter foraging and nesting tied to low vegetation density or leaf litter	*Insects:* Lassau and Hochuli 2004; Blaum *et al.* 2009 *Birds:* Wilson 1974; Ford *et al.* 1986; Watson *et al.* 2002 *Mammals*: Barnett *et al.* 1978, Catling and Burt 1995; Catling *et al.* 2000 *Reptiles:* Lunney *et al.* 1991; Brown 2001
Logs and coarse woody debris	Species using or avoiding logs and woody debris for nesting, shelter, and basking	*Birds*: Noske 1985; Watson *et al.* 2002 *Mammals*: Barnett *et al.* 1978 *Reptiles:* Garden *et al.* 2007
Log hollows	Species using or avoiding logs and woody debris for foraging, nesting, and shelter	*Mammals:* Christensen *et al.* 1984 *Reptiles:* Nichols and Bamford 1985
Tree hollows	Hollow using species with varying breeding and shelter requirements	*Bats:* Tidemann and Flavel 1987; Lunney *et al.* 1988 *Birds:* Saunders *et al.* 1982; Noske 1985; Luck 2002 *Mammals:* Lindenmayer *et al.* 1991; Pausas *et al.* 1995; Goldingay 2012
Tree stems	Species using or avoiding dense canopy foliage and vertical complexity	*Bats:* Lumsden *et al.* 2002; Adams *et al.* 2009 *Birds*: Recher *et al.* 1985; Ford *et al.* 1986; Mac Nally 1990; Pearce 1996 *Mammals*: Pausas *et al.* 1995; Munks *et al.* 1996; Soderquist and Mac Nally 2000 *Reptiles*: Lunney *et al.* 1991 *Insects:* Oliver *et al.* 2000
Tree canopy	Species using or avoiding dense canopy foliage and vertical complexity	*Reptiles:* Greenberg 2001; Webb *et al.* 2005; Pike *et al.* 2011 *Bats:* Law 1993; Adams *et al.* 2009 *Birds:* Recher 1969; Watson *et al.* 2002; Tassicker *et al.* 2006 *Insects*: York 2000

Habitat type	**Fauna habits/behaviour/use**	**References**
Habitat diversity: tree	Species presence correlated with lateral or vertical complexity, and diversity of tree and bark types	*Bats:* Lunney *et al.* 1998 *Birds:* Wilson 1974; Recher *et al.* 1985; Ford *et al.* 1986; Mac Nally 1990; Watson *et al.* 2002 *Mammals:* Pausas *et al.* 1995; Munks *et al.* 1996; Soderquist and Mac Nally 2000
Habitat diversity: shrub layer	Species using or avoiding dense low-level lateral cover, or requiring a range of sheltered and open habitats	*Reptiles:* Bonnet *et al.* 2016 *Mammals:* Bennett 1993; Fisher 2001; Le Mar and McArthur 2005; Swan *et al.* 2009; Fitzgibbon *et al.* 2010 *Insects:* York 2000; Blaum *et al.* 2009 *Birds*: Wilson 1974, Watson *et al.* 2002 *Bats:* Bringham *et al.* 1997; Rainho *et al.* 2010
Low shrub to lower part of canopy	Species using or avoiding dense low-level lateral cover, or require a range of sheltered and open habitats	*Mammals:* Fisher 2001; Le Mar and McArthur 2005; Di Stefano *et al.* 2009; Swan *et al.* 2009 *Birds:* Wilson 1974; Watson *et al.* 2002 *Bats:* Brown *et al.* 1997; Adams *et al.* 2009 *Reptiles:* Brown 2001

5.4 Results

5.4.1 Underlying differences among vegetation types and inter-fire interval groups

There were apparent differences in environmental factors and fire history among the vegetation types and interval groups (Figure 5.1*a*-*d*; Figure 5.2*a*-*h*)). In addition, the majority (45) of the most recent fires were prescribed and only nine were wild and the number of wildfires was not evenly spread through the interval groups (Figure 5.3). Therefore, I considered it important to account for fire history and environmental factors as predictors of the variation in habitat in subsequent analyses.

5.4.2 Derived habitat types

The Principal Component Analysis reduced 85 variables (Table 2.9) to 58 in 17 principal components (PC) for site level and six for the quadrat level, relating to the habitat types listed in Table 5.2 (Table 5.3). These PCs and six attributes were used as response variables in subsequent analyses.

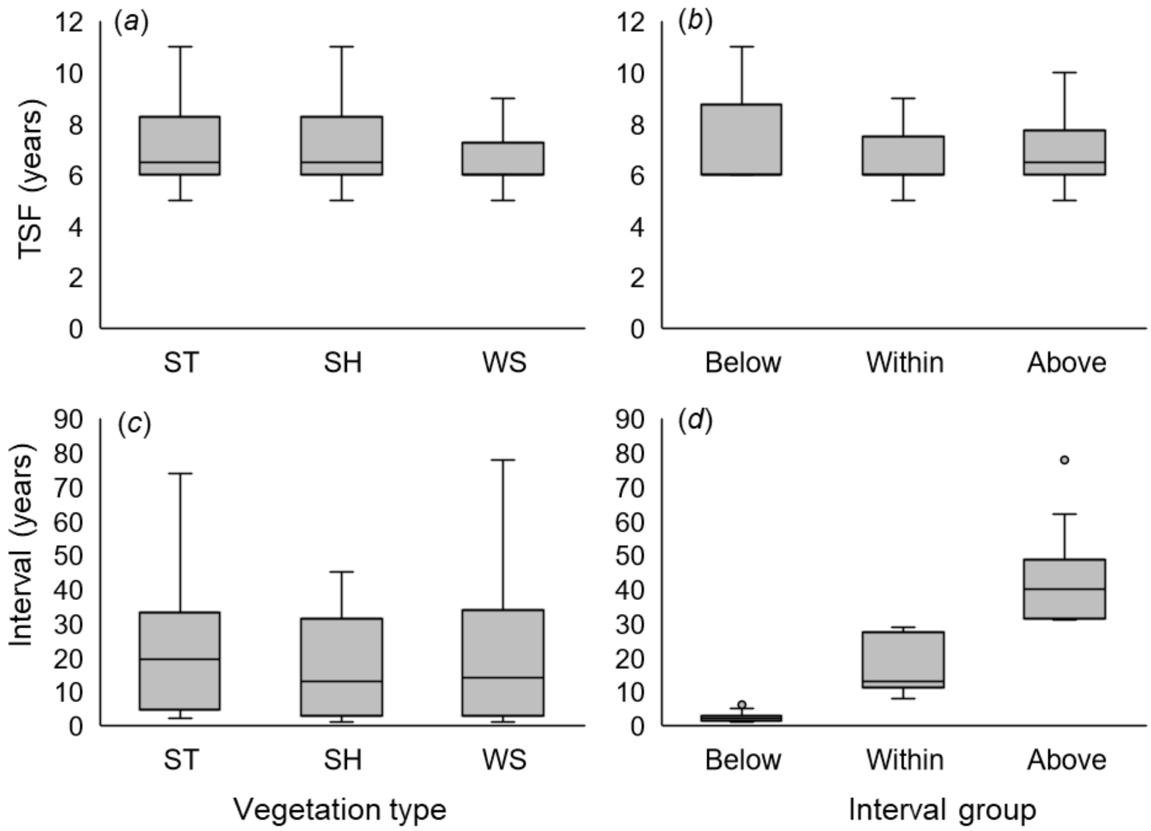


Figure 5.1 Comparison among Southern Tablelands (ST), Sydney Hinterland (SH), and Western Slopes (WS) Dry Sclerophyll Forests and interval groups (Below: less than minimum recommended interval; Within: the recommended interval; Above: longer than recommended interval) for time since the most recent fire (a and b); and years between the most recent fire and the fire before (Interval) (c and d). The horizontal middle line represents the median value, the shaded box represents the central 50% of data and the lines represent the lower and upper 25% of data. Circles designate outliers >1.5 times the interquartile range from the upper or lower quartile

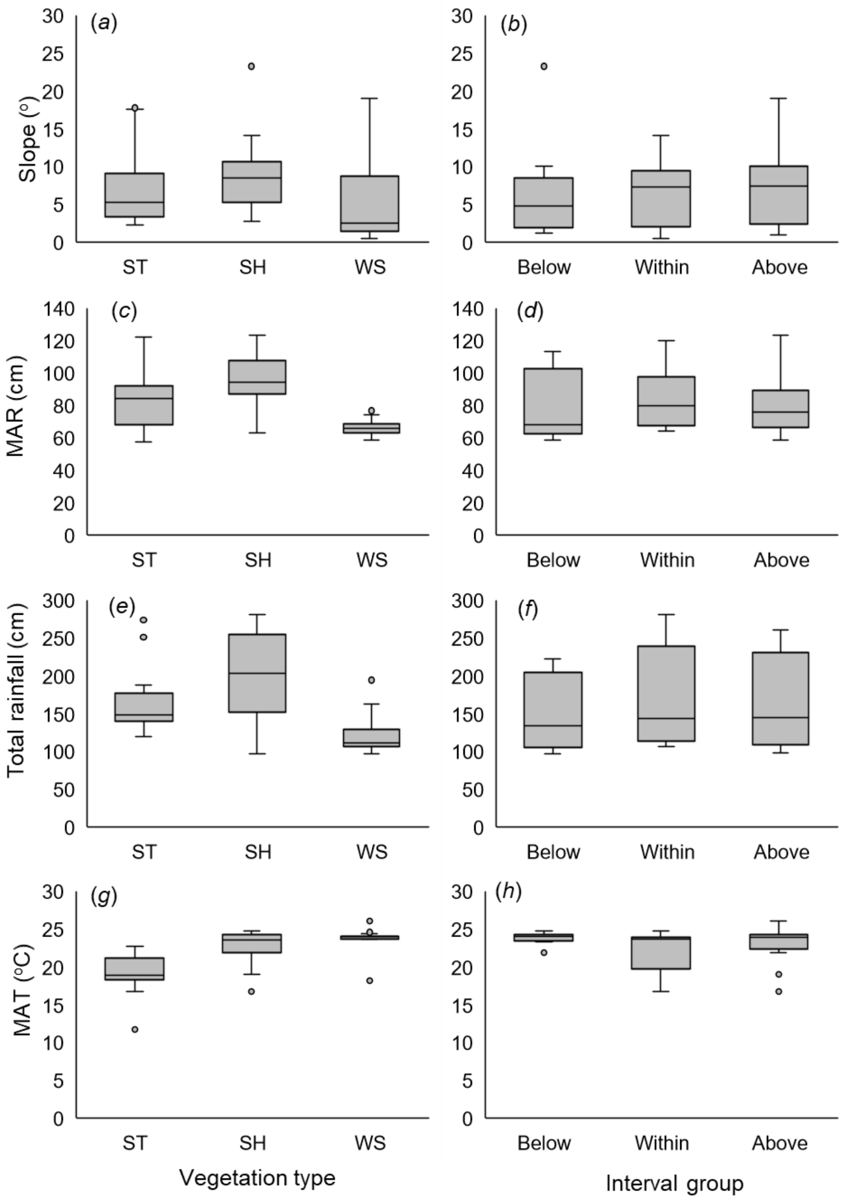


Figure 5.2 Comparison of slope, mean annual rainfall (MAR), total rainfall recorded in the 24 months post-fire (total rainfall) and mean annual temperature (MAT) among vegetation types (*a, c, e, g*; Southern Tablelands (ST), Sydney Hinterland (SH), and Western Slopes (WS)) and interval groups (*b, d, f, h*; Below: less than minimum recommended interval; Within: the recommended interval; Above: longer than recommended interval). The horizontal middle line represents the median value, the shaded box represents the central 50% of data and the lines represent the lower and upper 25% of data. Circles designate outliers >1.5 times the interquartile range from the upper or lower quartile

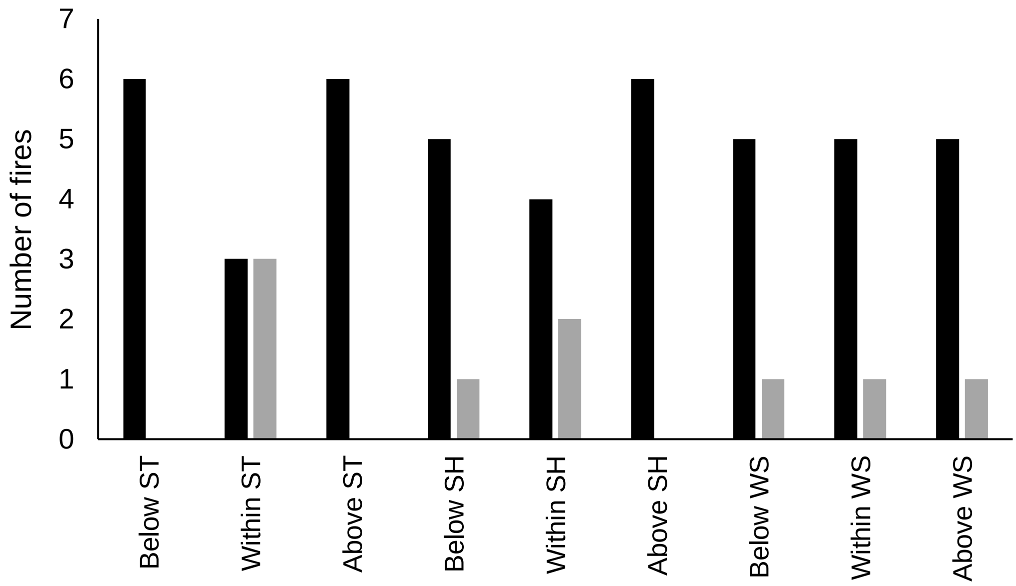


Figure 5.3 For the most recent fire at each site, the number that were prescribed (black) or wild (grey) in each combination of vegetation type (Southern Tablelands (ST), Sydney Hinterland (SH), and Western Slopes (WS) Dry Sclerophyll Forests) and interval groups (Below: less than minimum recommended interval; Within: the recommended interval; Above: longer than recommended interval)

Table 5.3. Principal components derived from habitat variables

For each habitat type at the site scale and the quadrat scale: the principal component (PC) name used in analyses; the habitat variables used to derive the PC; the proportion of each variables variance that is accounted for and the direction of the correlation; and the total variance explained by the PC. HAG = height above ground

Habitat type	Principal Component	Habitat variables used	Extraction	Variance explained
SITE SCALE				
Ground Cover (0-50 cm)	GndCov1(S)	Mean % veg 20-50cm (5 m)	0.938	56%
		Mean % veg 0-20 cm (5 m)	0.936	
		Mean % veg 0-20 cm (2 m)	0.930	
		Mean % veg 20-50cm (2 m)	0.928	
		Mean height near surface layer	0.594	
		Mean % cover plants	0.303	
	GndCov2(S)	Mean weight dried leaf litter	0.847	21%
		Mean % cover leaf litter	0.840	
		Mean % cover plants at ground level (<20 cm)	-0.718	
Logs and coarse woody debris (CWD)	LogCWD1(S)	Maximum HAG (CWD)	0.946	48%
		Mean HAG (CWD)	0.938	
		Total volume CWD (cm^3)	0.586	
	LogCWD2(S)	Total length log above ground	0.921	25%
		Total volume logs (cm^3)	0.809	
		Maximum HAG (logs)	0.695	
		Total volume CWD (cm^3)	0.424	
Log hollows	LogHol1(S)	Total no. hollow logs	0.989	86%
		Total no. hollows in logs	0.983	
		Total no. hollows <15 cm in logs	0.948	
		Total volume logs (cm^3)	0.762	
Tree hollows	TreeHol1(S)	Total no. trees with hollows	0.967	64%
		No. hollow size groups	0.958	
		No. hollows <15 cm	0.865	
		No. hollows >15 cm	0.845	
Tree stems	TreeStem1(S)	Diameter at breast height (1.3 m; DBH) of largest live tree	0.948	58%
		No. trees >60 cm DBH	0.888	

Habitat type	Principal Component	Habitat variables used	Extraction	Variance explained
		Mean DBH	0.839	
		No. DBH size groups	0.709	
	TreeStem2(S)	Total basal area dead trees	0.982	26%
		DBH of largest dead tree	0.977	
		No. DBH size groups	0.371	
Tree canopy	TreeCan1(S)	Mean tree height	0.947	70%
		Height of tallest tree	0.868	
		Height lowest live canopy or epicormic growth	0.661	
Habitat diversity - tree	TreeDiv1(S)	Std. dev. mean DBH	0.880	41%
		Std. dev. mean basal area	0.873	
		No. trees >60 cm DBH	0.772	
		No. DBH size groups	0.735	
	TreeDiv2(S)	No. trees with epicormic	0.915	22%
		Mean height epicormic	0.887	
		No. DBH size groups	0.367	
	TreeDiv3(S)	No. tree species	0.917	17%
		No. bark types	0.902	
Habitat diversity – shrub layer	ShrubDiv1(S)	Coefficient of Variation (CV) mean % veg 0.5-1m (2m)	0.903	51%
		CV mean % veg 1-1.5m (2 m)	0.837	
		CV mean % veg 20-50cm (2 m)	0.738	
		CV mean % veg 0.5-1m (5m)	0.611	
		CV mean % veg 1-1.5m (5 m)	0.400	
	ShrubDiv2(S)	CV mean % veg 0-20cm (5 m)	0.937	19%
		CV mean % veg 0-20cm (2 m)	0.811	
		CV mean % veg 20-50cm (5 m)	0.749	
		CV mean % veg 1-1.5m (5 m)	-0.556	
Low shrub to lower part of canopy	LowShrub1(S)	Mean % veg 0.5-1m (2 m)	0.946	34%
		Mean % veg 1-1.5m (5 m)	0.938	
		Mean % veg 0.5-1m (5 m)	0.921	
		Mean % veg 1-1.5m (2 m)	0.911	
		Total range of near surface /elevated/intermediate	0.651	
		Height difference between mid-canopy and canopy	-0.409	

Habitat type	Principal Component	Habitat variables used	Extraction	Variance explained
	LowShrub2(S)	Mean height epicormic growth	0.875	26%
		No. trees with epicormic	0.818	
		Height difference mid-canopy and canopy	-0.679	
		Height shortest tree	-0.542	
		Height lowest live canopy or epicormic growth	-0.511	
	LowShrub3(S)	Mean length of basal regrowth	0.969	13%
		Total length of basal regrowth	0.967	
		Height lowest live canopy or epicormic growth	-0.474	
QUADRAT SCALE				
Ground Cover (0-50 cm)	GndCov1(Q)	Mean % veg 20-50cm (5 m)	0.889	45%
		Mean % veg 0-20 cm (2 m)	0.889	
		Mean % veg 0-20 cm (5 m)	0.874	
		Mean % veg 20-50cm (2 m)	0.861	
		Mean height near surface layer	0.410	
	GndCov2(Q)	Mean % cover leaf litter	0.795	18%
		Mean weight dried leaf litter	0.721	
		Mean % cover plants	-0.688	
Logs and coarse woody debris	Log1(Q)	Total length scorched logs	0.899	73%
		Mean length scorched logs	0.866	
		Total volume logs (cm^3)	0.859	
		Total length log above ground	0.834	
		Maximum HAG (logs)	0.811	
Low shrub to lower part of canopy	LowShrub1(Q)	Mean % veg 0.5-1m (2 m)	0.934	33%
		Mean % veg 1-1.5m (5 m)	0.917	
		Mean % veg 0.5-1m (5 m)	0.876	
		Mean % veg 1-1.5m (2 m)	0.871	
	LowShrub2(Q)	Height of lowest live canopy or epicormic growth	-0.858	27%
		No. trees with epicormic	0.835	
		Mean height epicormic growth	0.780	
		Height difference mid-canopy and canopy	0.768	
		Height difference canopy	0.749	
	LowShrub3(Q)	Total length of basal regrowth	0.956	13%
		Mean length of basal regrowth	0.956	
		Highest tree scorching	0.408	

5.4.3 Predictors of differences in habitat

Vegetation type was the most common predictor overall and was a significant predictor for most models for both the site and quadrat level (Table 5.4; Table 5.5). By comparison, interval group was a significant predictor for only three of the models, all at a site scale.

5.4.3.1 Ground Cover

The best ranked model used vegetation type and the total number of stems on a site to explain GndCov1(S) (Table 5.4). This indicated denser low (<50cm) vegetation cover in Southern Tablelands and Sydney Hinterland than Western Slopes but no difference between Southern Tablelands and Sydney Hinterland (Table 5.4; Table 5.3; Cohen’s effect size: Western Slopes vs Sydney Hinterland d = -0.8; Figure 5.4). There was a slight decrease of shrub cover with an increasing number of stems (Table 5.4; Figure 5.4) however, there was not a strong effect for total stems. The second-best ranked model used vegetation type and the total volume of logs on a site to explain GndCov1(S), which increased with increasing total volume of logs (Table 5.4; Figure A4.1). The best ranked model excluding vegetation type used mean annual rainfall (MAR) and longitude and showed GndCov1(S) increasing with increasing MAR and being highest in eastern NSW (Figure A4.2).

At a quadrat level, vegetation type best explained GndCov1(Q) indicating significantly less dense low (<50 cm) shrub cover in Western Slopes than Southern Tablelands and Sydney Hinterland but no difference in Southern Tablelands and Sydney Hinterland (Table 5.4; Table 5.3; Cohen’s effect size: Western Slopes vs Sydney Hinterland: d = -1.09; Figure 5.5). The total volume of logs on a quadrat was also a strong predictor when added to the model and showed low shrub cover increasing with increasing total volume of logs (Table 5.5; Figure A4.3). The best ranked model excluding vegetation type used longitude to explain GndCov1(Q) which was highest in eastern NSW (Table 5.5; Figure A4.4).

Mean annual rainfall and longitude best explained GndCov2(S), indicating increased leaf litter and decreased plant cover on the ground with increasing rainfall and in the east (Table 5.4; Figure A4.5). At a quadrat level, vegetation type interacting with fire type, plus latitude, the total number of logs, and the total number of stems best explained GndCov2(Q). This indicates greater cover and mass of leaf litter and less plant cover at ground level in northern NSW and with increasing number of logs and stems (Table 5.5; Figure A4.6). There was no distinguishable impact of a prescribed fire among vegetation types, but GndCov2(S) was significantly lower in Western Slopes after a wildfire (Table 5.5). The best ranked model excluding vegetation type used the total number of tree stems to best explain GndCov2(Q) which increased with increasing stems (Table 5.5; Figure A4.7).

5.4.3.2 Logs and coarse woody debris (CWD)

The best-ranked model used fire interval groups, mean annual rainfall, and mean tree DBH to explain LogCWD1(S) and showed volume and height above ground of coarse woody debris increasing with increasing mean annual rainfall and decreasing with increasing mean tree DBH. Volume and height above ground of coarse woody debris was greatest in sites below recommended intervals but decreased significantly in sites within recommended intervals. There was a marginal decrease in height above ground and volume of coarse woody debris for sites with time between fires longer than the recommended interval (Table 5.4; Figure 5.6).

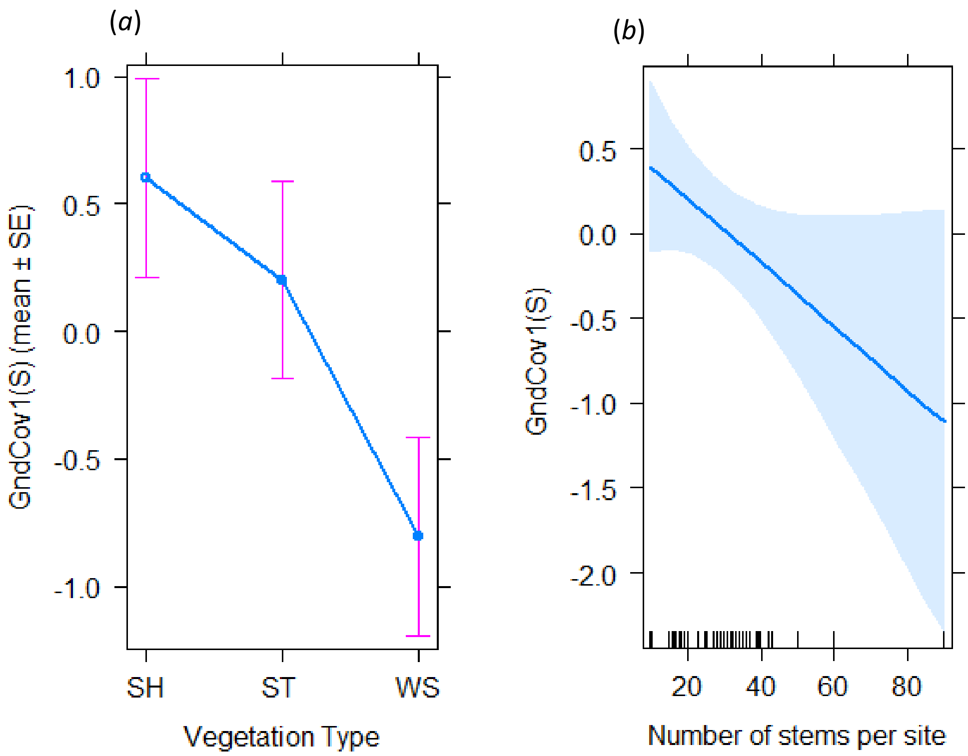


Figure 5.4 Effect plots for the preferred GLM for the principal component GndCov1(S): (a) vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes); and (b) the number of tree stems on a site. Explanations of principal components are in Table 5.3

Vegetation type best explained LogCWD2(S) indicating a greater volume and length of logs in Southern Tablelands than in Sydney Hinterlands (Table 5.4; Table 5.3; Cohen's effect size: Sydney Hinterlands vs Southern Tablelands: *d* = -1.1; Figure A4.8). The second best-ranked model used mean annual temperature and showed volume and length of logs decreasing with increasing temperature (Table 5.4; Figure A4.9). Vegetation type also best explained Log1(Q) at a quadrat level indicating the volume, height and scorch length of logs was lower in Southern Tablelands but similar in Sydney Hinterland and Western Slopes (Table 5.5; Table 5.3; Cohen's effect size: Western Slopes vs Southern

Tablelands: *d* = -0.3; Figure A4.10). The second best-ranked model used mean annual temperature and showed Log1(Q) decreasing with increasing temperature (Table 5.5; Figure A4.11).

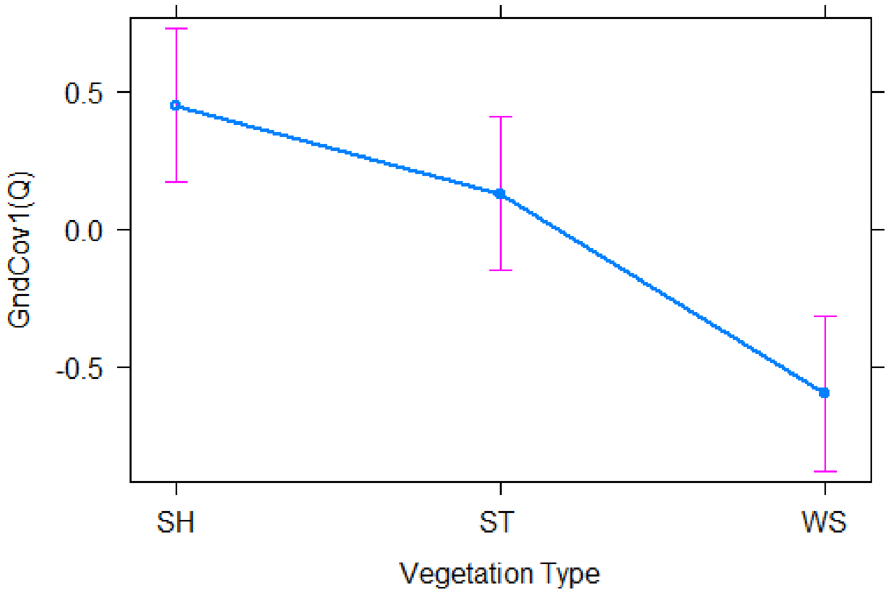


Figure 5.5 Effect plots for the preferred GLMM for the principal component GndCov1(Q) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

Vegetation type and fire type with an interaction, plus TreeStem2(S) best explained the total volume of logs, indicating increased volume of logs with increased numbers of DBH size classes and basal area of dead trees. There were no significant impacts of a wildfire detected however, the volume of logs was significantly lower in Sydney Hinterlands and Western Slopes than Southern Tablelands when the most recent fire was a prescribed fire (Table 5.4; Figure 5.7). The proportion of logs with scorching on a site was best explained by latitude, which increased from north to south (Table 5.4; Figure A4.12).

The total length of scorched logs decreased with increasing mean annual temperature (Table 5.4; Figure A4.13).

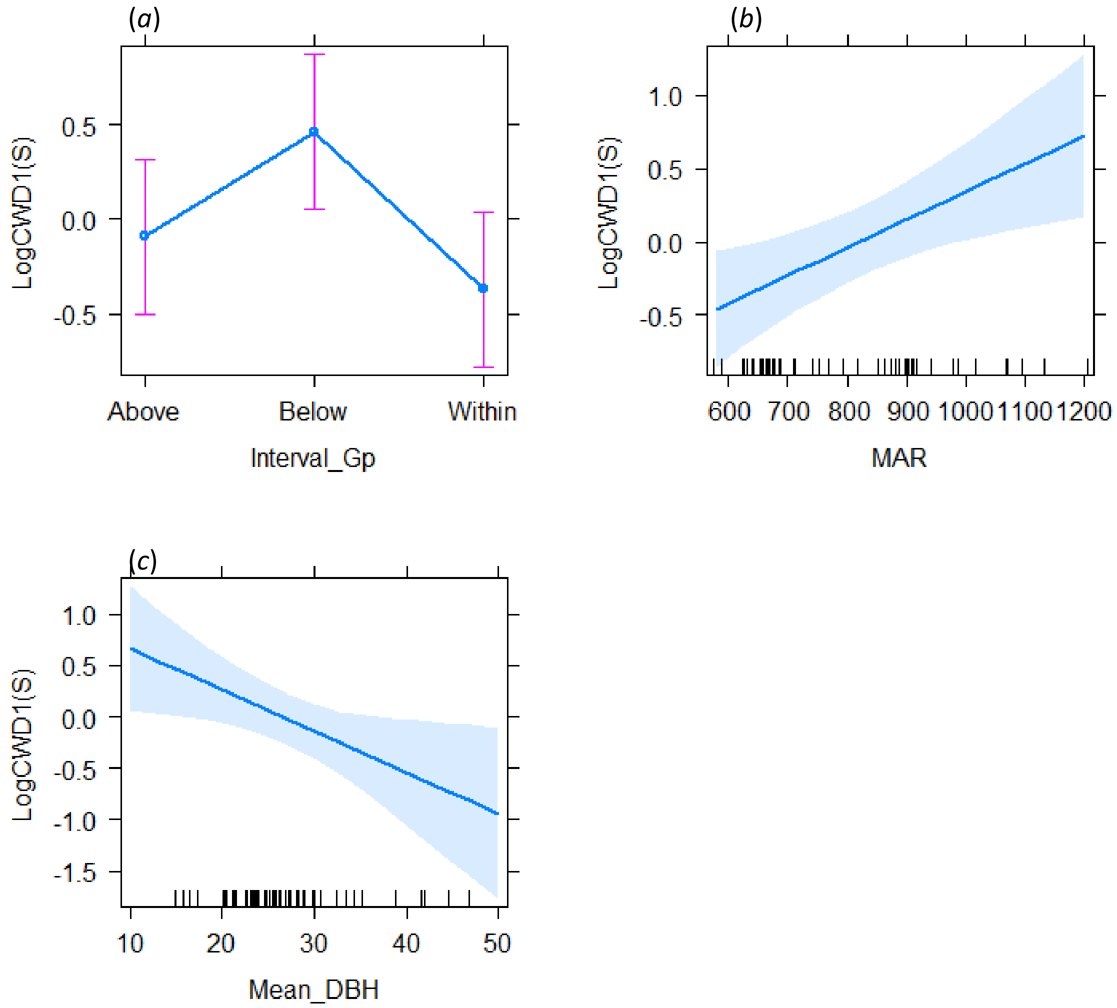


Figure 5.6 Effect plots for the preferred GLM for the principal component LogCWD1(S): (*a*) interval group (Interval_Gp: (below) = below minimum recommended intervals; interval (within) = within recommended intervals; interval (above) = above recommended intervals); (*b*) mean annual rainfall (MAR; mm); and (*c*) the mean DBH of trees on a site (mm). Explanations of the principal components are in Table 5.3

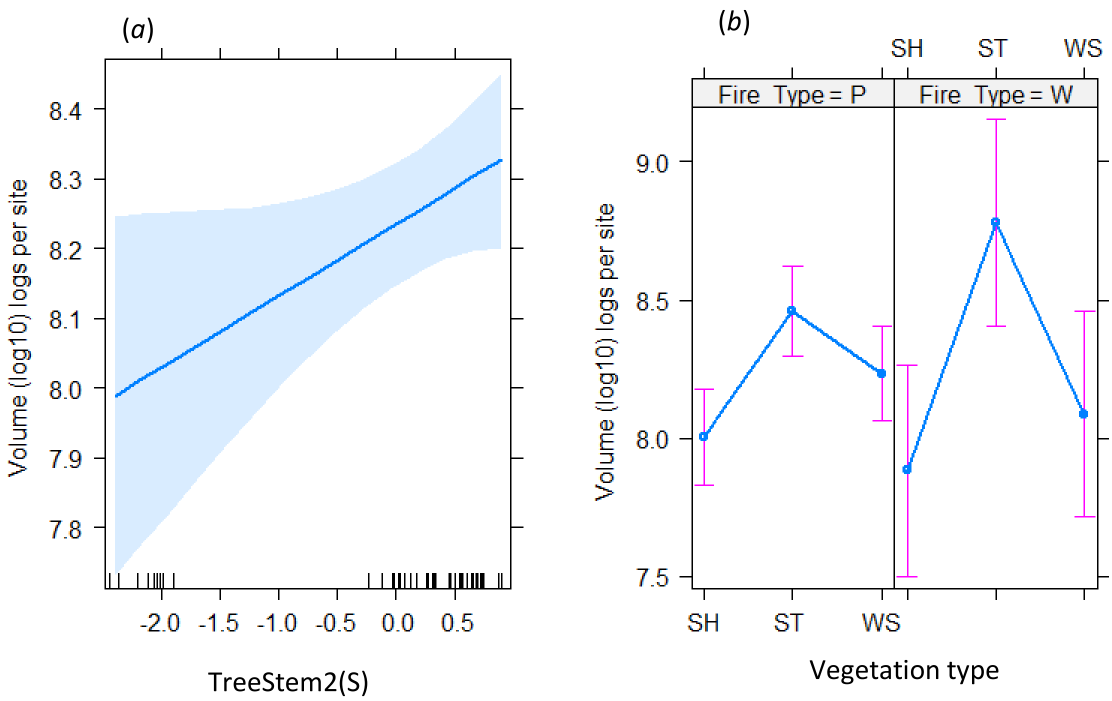


Figure 5.7 Effect plots for the preferred GLM for the total volume of logs (cm^3) on a site: (*a*) TreeStem2(S); and (*b*) fire type (p = prescribed, w = wild) and an interaction with vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes). Explanations of the principal components are in Table 5.3

5.4.3.3 Hollows in logs and trees

Vegetation type and an interaction with interval groups, plus mean annual rainfall and mean annual temperature best explained LogHol1(S) which decreased with increasing rainfall and temperature. Log volume and number of hollows in logs were lower in Sydney Hinterlands and marginally so in Western Slopes than in Southern Tablelands sites in the below and within recommended interval sites. However, log volume and number of hollows in logs increased in Sydney Hinterland and Western Slopes and decreased in Southern Tablelands as the time between fires increased to above the recommended interval (Table 5.4; Figure A4.14). The best model excluding vegetation type included only the total basal area of dead trees to explain LogHol1(S) (Table 5.4; Figure A4.15). The best model used the total basal area of live trees to explain the likelihood of a large (≥15 cm) log hollow on a site indicating increased presence of large log hollows with increasing basal area (Table 5.4; Figure A4.16).

Vegetation type, mean annual temperature, and the number of DBH size classes best explained TreeHol1(S) which decreased with mean annual temperature and increased with increasing variation in DBH of trees. The model also indicates that number of hollows and the variation in sizes of hollows differed among vegetation types and were less in Sydney Hinterlands and Western Slopes than in Southern Tablelands (Table 5.4; Table 5.3; Cohen's effect size: Western Slopes vs Southern Tablelands $d = 1.5$; Figure A4.17). The best-ranked model excluding vegetation type used mean annual temperature only and showed TreeHol1(S) decreasing with increasing temperature (Table 5.4; Figure A4.18). The best predictor of the likelihood of a large (≥15 cm) tree hollow on a site used mean annual temperature only and showed a decreased likelihood with increasing temperature (Table 5.4; Figure A4.19).

5.4.3.4 Tree stems and canopy

The best-ranked model to explain TreeStem1(S) used vegetation type with larger trees and number of DBH size classes in Sydney Hinterland and lower in Southern Tablelands than Western Slopes (Table 5.4; Table 5.3; Figure A4.20). The best ranked model excluding vegetation type used mean annual temperature to explain TreeStem1(S) which decreased with increasing temperature (Table 5.4; Figure A4.21).

Vegetation type best explained TreeStem2(S) indicating basal area and DBH of dead trees and the number of DBH size classes were significantly lower in Sydney Hinterlands than Southern Tablelands and Western Slopes (Table 5.4; Table 5.3; Cohen's effect size: Sydney Hinterlands vs Southern Tablelands $d = -0.8$; Figure A4.22). The second-best ranked model used mean annual rainfall and showed TreeStem2(S) decreasing with increasing rainfall (Table 5.4; Figure A4.23). No models supported fire or environmental effect variables as predictors of TreeStem2(S). The best model to explain the likelihood of large trees (DBH ≥ 60cm) on a site used vegetation class with significantly fewer large trees in Sydney Hinterland than Southern Tablelands or Western Slopes (Table 5.4; Cohen's effect size: Sydney Hinterland vs Southern Tablelands *d* = -0.8; Figure A4.24).

The best-ranked model used vegetation type and an interaction with the total rainfall recorded from 2013-2020, and total tree basal area to explain TreeCan1(S), which increased with increasing total tree basal area and decreased significantly in Sydney Hinterlands and Western Slopes but increased slightly but not significantly in Southern Tablelands with increasing total rainfall (Table 5.4; Figure A4.25).

Fire type was the best predictor of the proportion of stems with scorching on a site, with significantly more scorched stems after wildfire than prescribed (Table 5.4; Figure A4.26). Adding interval group to the model showed a significant decrease in the proportion of scorched stems in the within recommended interval sites compared to the below recommended interval sites, but a slight increase as the interval between fires moved to above the recommended intervals (Table 5.4; Figure A4.27).

5.4.3.5 Tree and shrub diversity

Vegetation type best explained TreeDiv1(S), indicating a greater variation in tree DBH and basal area in Southern Tablelands than Sydney Hinterlands and Western Slopes but no difference between Sydney Hinterlands and Western Slopes (Table 5.4; Table 5.3; Cohen's effect size: Sydney Hinterlands vs Southern Tablelands *d* = 7.7; Figure A4.28). The second-best ranked model used mean annual temperature (P = 0.023) and showed TreeDiv1 decreasing with increasing temperature (Table 5.4; Figure A4.29).

Vegetation type and an interaction with the total number of scorched stems and mean annual rainfall best predicted TreeDiv2(S), which decreased with increasing rainfall. This model indicates that number of DBH size classes and epicormic growth were significantly lower on Sydney Hinterlands than Southern Tablelands and Western Slopes. TreeDiv2(S) increased with the number of scorched stems in Sydney Hinterlands and Western Slopes but not significantly so in Western Slopes and did not change in Southern Tablelands (Table 5.4; Figure A4.30). No models supported fire or environmental effect variables as predictors of TreeDiv2(S).

Vegetation type best explained TreeDiv3(S) which was similar in Southern Tablelands and Western Slopes but significantly higher in Sydney Hinterlands (Table 5.4; Figure A4.31). The best-ranked model excluding vegetation type used mean annual rainfall to explain TreeDiv3(S) indicating increased tree species number and number of bark types with increasing rainfall (Table 5.4; Figure A4.32).

The best-ranked model used mean annual rainfall to explain ShrubDiv1(S), which decreased with increasing rainfall (Table 5.4; Figure A4.33). The second best-ranked model used vegetation type and an interaction with fire type and mean annual rainfall and showed a decrease with increasing rainfall. The effects of a prescribed fire were distinguishable in Southern Tablelands but not in Western Slopes and Southern Tablelands. The effects of a wildfire were distinguishable only in Southern Tablelands (Table 5.4; Figure 5.8). The best model predicting ShrubDiv2(S) showed increase with increasing volume and height above ground of logs (LogCWD2(S)) (Table 5.4; Figure A4.34).

The best-ranked model to explain LowShrub1(S) used TreeStem2(S) and mean annual rainfall. This model showed a decrease in LowShrub1(S) with increase in TreeStem2(S) (number of DBH size classes and basal area), but an increase with increasing rainfall (Table 5.4; Figure A4.35). The second-best ranked model used rainfall and showed an increase in LoswShrub1(S) with increasing rainfall (Table 5.4; Figure A4.36). At a quadrat level, vegetation type best described LowShrub1(Q) and was significantly higher in Southern Tablelands but similar in Western Slopes and Sydney Hinterland (Table 5.5; Figure A4.37). The best-ranked model excluding vegetation type used mean annual rainfall and showed an increase with increasing rainfall (Table 5.5; Figure A4.38).

The total number of scorched stems and mean annual temperature best explained LowShrub2(S), which increased as the number of scorched stems increased and decreased with increasing temperature (Table 5.4; Figure A4.39). At a quadrat level, the best-ranked model used the total number of scorched stems to explain LowShrub2(Q), which increased as the number of scorched stems increased (Table 5.5; Figure A4.40). Adding vegetation type to the model increased the AIC by 1.33 points and showed LowShrub2(Q) was significantly lower in Sydney Hinterlands than Southern Tablelands and Western Slopes (Table 5.5; Figure A4.41).

Fire type best explained LowShrub3(S) indicating the heights of basal regrowth and the lower part of the canopy were greater after wildfire than prescribed, however the effect was only marginal (Table 5.4; Table 5.3; Cohen's effect size: prescribed vs wild d = -0.7; Figure 5.9). At a quadrat level, fire type also best explained LowShrub3(Q) which was significantly higher after a wildfire than a prescribed (Table 5.5; Table 5.3; Figure A4.42).

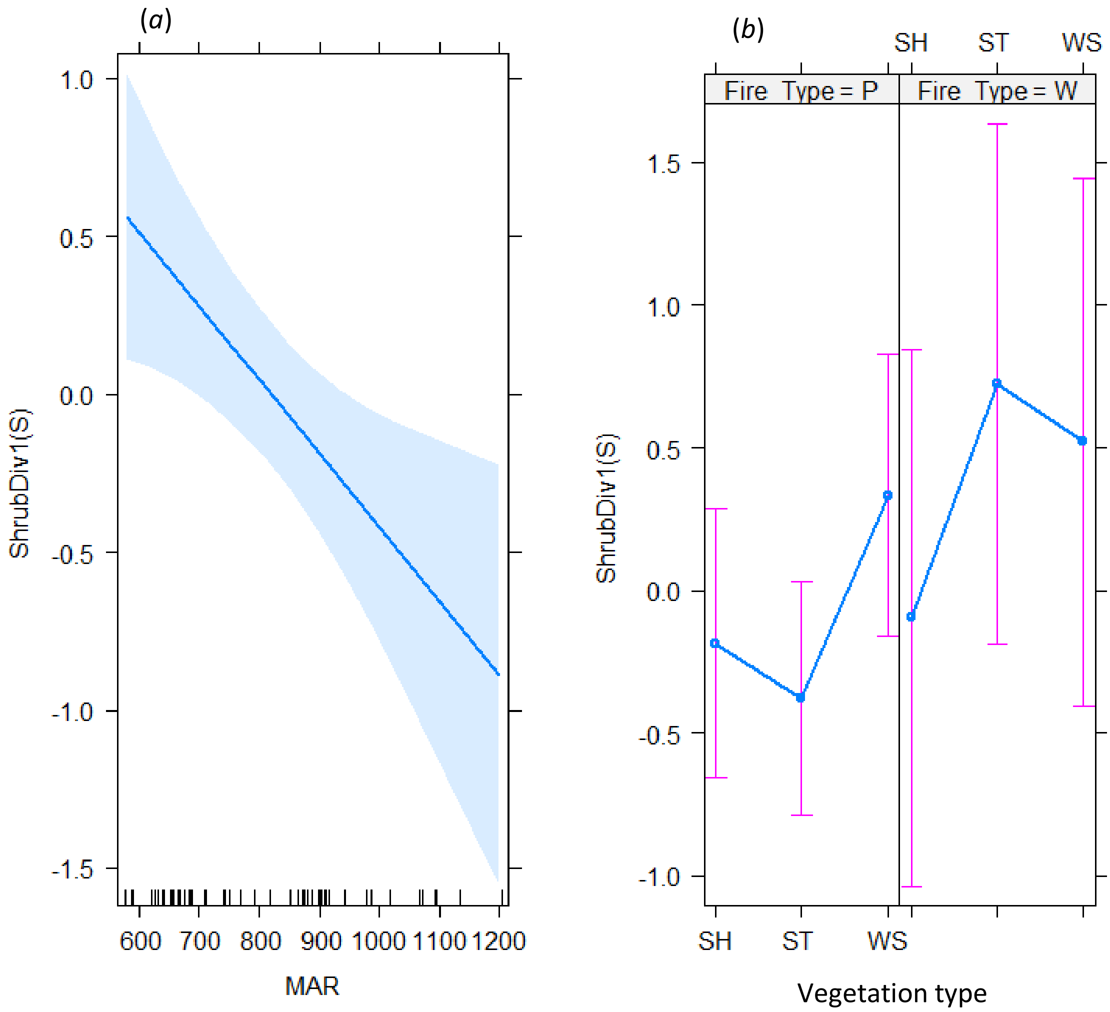


Figure 5.8 Effects plot for the alternate GLM for ShrubDiv1(S): (*a*) mean annual rainfall (MAR, mm); and (*b*) fire type (p = prescribed, w = wild) interacting with vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes). Explanations of the principal components are in Table 5.3

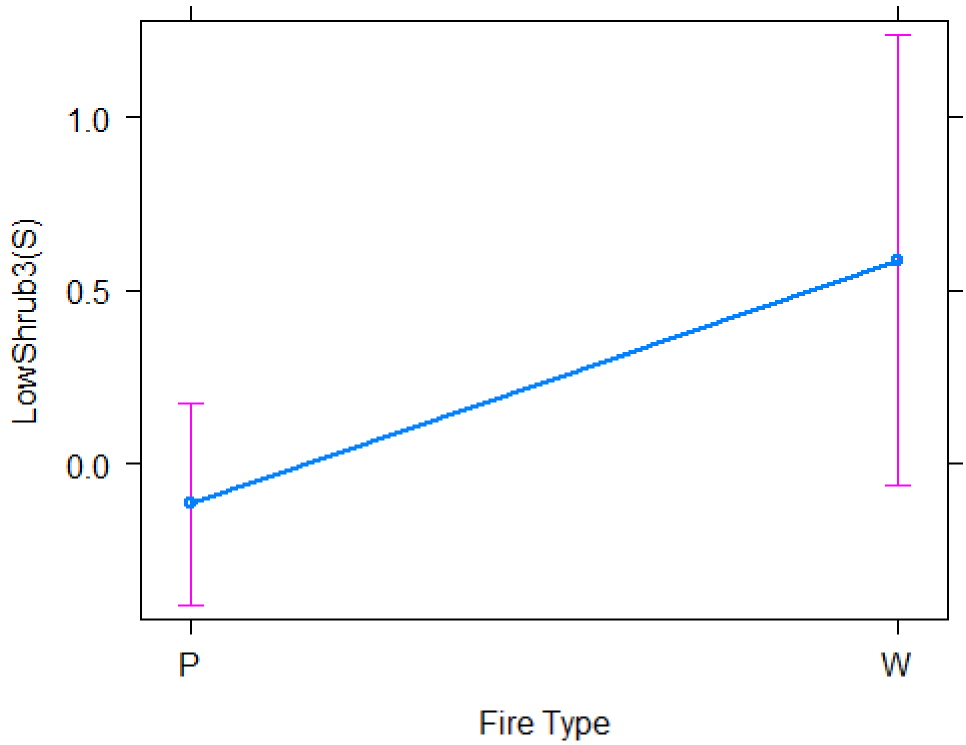


Figure 5.9 Effect plot for the preferred GLM for LowShrub3(S) showing fire type (p = prescribed, w = wild) as the best predictor. Explanations of the principal components are in Table 5.3

Although fire type did not have a strong effect in most models, there was a large variance around the mean for many of the response variables. Apparent differences in variance between wild and prescribed fires were mostly accounted for by a difference in sample size (n = 9 for wildfire; n =45 for prescribed). However, there was a greater variation in the total volume of logs on a site after wildfire than after prescribed fire (Levene's test for homogeneity of variances: $F_{1,52} = 8.773$, $P = 0.005$; Figure 5.10). For the remaining habitat types and variables, there was no significant differences in the variance associated with the mean for wild and prescribed fires (Levene's test: $P > 0.05$).

Interval groups (below, within, above recommended interval) was only a significant predictor in three of the best-ranked models at a site level and no models at a quadrat level (Table 5.4; Table 5.5**)**. Using the actual number of years between the most recent fire and the fire before (actual value of inter-fire interval) was not a significant predictor in any of the models. Aspect, slope, and hydrological soils groups were not included as predictors of habitat types or variables in any of the best-ranked models.

Transect as a random effect in the GLMM models accounted for at most three orders of magnitude less than the contribution of site, and as such I excluded transect as an effect.

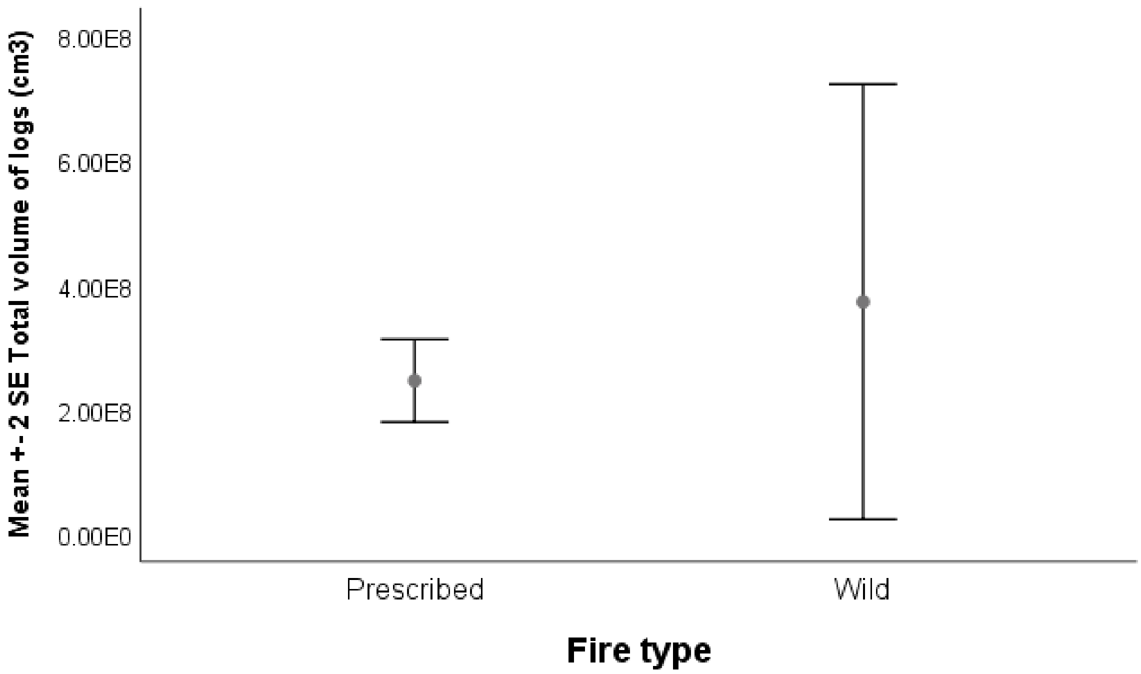


Figure 5.10 The variation in values around the mean (±2 SE) for the total volume of logs at a site after a prescribed or wildfire

5.4.4 Proximal similarities among sites

There were spatial correlations for six habitat types or variables, demonstrating that values for those variables were more similar in sites that were geographically close, but not necessarily in the same vegetation type. Four habitat types and variables representing ground and low shrub cover showed positive spatial correlations: GndCov1(S), GndCov2(S), ShrubDiv1(S), and total volume of logs. Two habitat types representing hollows showed positive spatial correlations: LogHol1 and TreeHol1. The remaining habitat types were not spatially correlated (Table 5.6).

Table 5.4. Generalised Linear Model output at site level

GLM fixed effects results for each habitat type at a site level showing the relationship with the strongest environmental or fire history predictor, the adjustment to the intercept for vegetation type or predictor variable, the null and residual deviance, and the amount of variance explained by the model (R^2). Fire type W = wildfire; Fire type P = prescribed fire; interval (below) = below minimum recommended intervals; interval (within) = within recommended intervals; interval (above) = above recommended intervals; vegetation types: ST = Southern Tablelands (reference for vegetation type); SH = Sydney Hinterlands; WS = Western Slopes. MAR = mean annual rainfall; MAT = mean annual temperature; DBH = diameter at breast height (1.3 m). Explanations of principal components are in Table 5.3

Habitat Types		Estimate	SE	Df	t value	P	Null deviance	Residual deviance	R^2
Ground cover									
GndCov1(S)	Intercept	2.150	1.028	31.823	2.092	0.042	53	31.8	0.40
	SH	0.261	0.275		0.947	0.348			
	WS	-1.053	0.267		-3.942	<0.001			
	Total stems	-1.282	0.665		-1.920	0.056			
GndCov1(S)	Intercept	-6.239	2.840	30.987	-2.197	0.033	53	30.9	0.38
(Δ AIC +1.45)	SH	0.864	0.333		2.594	0.012			
	WS	-0.793	0.279		-2.848	0.006			
	Total volume logs	0.755	0.332		2.273	0.027			
GndCov1(S)	Intercept	-2.053	0.570	42.006	-3.603	<0.001	53	42	0.21
(Δ AIC +11)	MAR	0.003	<0.001		3.689	<0.001			

Habitat Types		Estimate	SE	Df	t value	P	Null deviance	Residual deviance	R^2
GndCov2(S)	Intercept	-7.105	2.001	36.702	-3.542	<0.001	53	37	0.31
	MAR	-2.001	6.001		-4.234	<0.001			
	Longitude	4.091	1.035		3.624	<0.001			
Logs and CWD									
LogCWD1(S)	Intercept (below)	2.668	1.727	36.779	1.545	0.129	53	37	0.31
	Interval (within)	-0.816	0.289		-2.823	0.007			
	Interval (above)	-0.560	0.290		-1.932	0.059			
	MAR	0.002	0.001		2.735	0.009			
	Mean DBH	-2.584	1.123		-2.300	0.026			
LogCWD2(S)	Intercept	0.404	0.225	46.515	1.797	0.078	53	47	0.12
	SH	-0.846	0.318		-2.659	0.011			
	WS	-0.367	0.318		-1.152	0.255			
LogCWD2(S) (Δ AIC +0.68)	Intercept	2.037	0.983	48.887	2.073	0.043	53	49	0.08
	MAT	-0.094	0.045		-2.092	0.041			
Total volume of logs	Intercept	8.460	0.081	4.714	10.234	<0.001	<0.001	<0.001	0.43
	SH	-0.457	0.120		-3.802	<0.001			
	WS	-0.227	0.117		-1.946	0.058			
	Fire type W	0.321	0.202		1.587	0.119			
	TreeStem2	0.103	0.050		2.043	0.047			
	SH * Fire type W	-0.442	0.289		-1.532	0.132			
	WS * Fire type W	-0.466	0.284		-1.639	0.108			
Proportion of logs with scorching	Intercept	-1.349	0.471	1.369	-2.864	0.006	2.4	1.9	0.20
	Latitude	-0.064	0.014		-4.554	<0.001			

Habitat Types		Estimate	SE	Df	t value	P	Null deviance	Residual deviance	R^2
Total length of scorched logs	Intercept	4.568	0.291	4.290	15.691	<0.001			
	MAT	-0.010	0.013		-3.082	0.003	110256	100404	0.09
Hollows in logs and trees									
LogHol1(S)	Intercept	2.725	0.809	26.279	3.370	0.002	53	23	0.56
	SH	-1.571	0.449		-3.497	0.001			
	WS	-1.331	0.493		-2.697	0.010			
	Interval (within)	-0.140	0.447		-0.312	0.756			
	Interval (over)	-0.833	0.459		-1.814	0.077			
	MAR	-0.002	0.001		-2.700	0.010			
	MAT	-0.117	0.049		-3.201	0.003			
	SH * Interval (within)	0.314	0.635		0.494	0.624			
	WS * Interval (within)	0.269	0.635		0.424	0.673			
	SH * Interval (above)	1.383	0.639		2.163	0.036			
	WS * Interval (above)	1.793	0.645		2.781	0.008			
LogHol1(S)	Intercept	-0.023	0.017	48.662	-1.362	0.179	53	49	0.08
(Δ AIC +22)	Total basal (dead)	<0.001	<0.001		2.153	0.036			
Large log hollows	Intercept	-0.001	7.054	69.789	-1.843	0.065	13	12	0.09
(≥15 cm)	Total basal area	<0.001	<0.001		2.067	0.039			
TreeHol1(S)	Intercept	-0.098	1.118	22.457	-0.088	0.930	53	21	0.60
	SH	-0.724	0.268		-2.696	0.010			
	WS	-0.571	0.283		-2.021	0.049			
	MAT	-0.116	0.040		-2.897	0.006			
	No. DBH size classes	4.472	1.108		4.037	<0.001			

Habitat Types		Estimate	SE	Df	t value	P	Null deviance	Residual deviance	R^2
TreeHol1(S)	Intercept	4.181	0.840	35.676	4.980	<0.001	53	36	0.33
(Δ AIC +22)	MAT	-0.193	0.038		-5.025	<0.001			
Large tree hollows	Intercept	6.433	2.844	70.047	2.262	0.024	12	11	0.08
(≥15 cm)	MAT	-0.263	0.126		-2.094	0.036			
Tree stems and canopy									
TreeStem1(S)	Intercept	0.612	0.216	42.844	2.834	0.007	53	43	0.19
	SH	-0.948	0.306		-3.104	0.003			
	WS	-0.888	0.306		-2.909	0.005			
TreeStem1(S)	Intercept	2.217	0.975	48.13	2.273	0.027	53	48	0.09
(Δ AIC +4.3)	MAT	-0.102	0.044		-2.294	0.026			
TreeStem2(S)	Intercept	0.202	0.212	41.355	0.950	0.347	53	41	0.22
	SH	-0.844	0.300		-2.811	0.007			
	WS	0.239	0.300		0.795	0.430			
TreeStem2(S)	Intercept	1.921	0.579	43.369	3.319	0.002	53	43	0.18
(Δ AIC +0.57)	MAR	-0.002	<0.001		-3.398	0.001			
Large (DBH ≥	Intercept	0.693	0.500	66.715	1.386	0.166	13	13	0.03
60cm) trees	SH	-1.946	0.756		-2.574	0.010			
	WS	-0.916	0.689		-1.329	0.184			
TreeCan1(S)	Intercept	-6.690	2.953	35.994	-2.265	0.028	53	35	0.34
	SH	2.708	1.337		2.025	0.049			
	WS	4.181	1.970		2.122	0.039			

Habitat Types		Estimate	SE	Df	t value	P	Null deviance	Residual deviance	R^2
	Total rain 2013-2020	<0.001	<0.001		1.014	0.316			
	Total basal area	1.396	0.675		2.068	0.044			
	Total rain 2013-2020 * SH	-0.001	<0.001		-2.253	0.029			
	Total rain 2013-2020 * WS	-0.001	<0.001		-2.120	0.039			
Proportion of stems with scorching	Intercept	0.156	0.010	0.250	15.133	<0.001	3	2.7	0.11
	Fire type W	0.061	0.025		2.407	0.020			
Proportion of stems with scorching (Δ AIC +0.74)	Intercept	0.181	0.016	0.230	11.146	<0.001	3	2.5	0.18
	Fire type W	0.071	0.026		2.737	0.009			
	Interval (within)	-0.048	0.023		-2.038	0.047			
	Interval (above)	-0.030	0.023		-1.392	0.170			
Tree and shrub diversity									
TreeDiv1(S)	Intercept	0.535	0.222	45.105	2.411	0.019	53	45	0.15
	SH	-0.873	0.314		-2.785	0.008			
	WS	-0.731	0.314		-2.330	0.024			
TreeDiv1(S) (Δ AIC +1.3)	Intercept	2.260	0.973	47.939	2.322	0.024	53	48	0.10
	MAT	-0.104	0.044		-2.343	0.023			
TreeDiv2(S)	Intercept	-1.847	1.479	34.85	-1.242	0.221	53	35	0.34
	SH	3.651	1.504		2.427	0.019			
	WS	1.237	1.469		0.842	0.404			
	Scorched stems	2.985	1.091		2.737	0.009			
	MAR	-0.002	<0.001		-2.204	0.032			
	SH * Scorched stems	-2.784	1.278		-2.178	0.034			
	WS * Scorched stems	-1.146	1.290		-0.889	0.379			

Habitat Types		Estimate	SE	Df	t value	P	Null deviance	Residual deviance	R^2
TreeDiv3(S)	Intercept	-0.294	0.217	43.301	-1.354	0.182	53	43	0.18
	SH	0.089	0.307		2.909	0.005			
	WS	-0.011	0.307		-0.036	0.971			
TreeDiv3(S) (Δ AIC +4.1)	Intercept	-1.322	0.612	48.443	-2.160	0.035	53	48	0.09
	MAR	0.002	<0.001		2.212	0.031			
ShrubDiv1(S)	Intercept	2.705	0.512	33.920	5.282	<0.001	53	34	0.36
	MAR	-0.003	0.001		-5.408	<0.001			
ShrubDiv1(S) (Δ AIC +1.1)	Intercept	1.542	0.724	28.776	2.128	0.039	53	29	0.46
	SH	0.193	0.302		0.639	0.526			
	WS	0.711	0.327		2.172	0.035			
	Fire type W	1.104	0.498		2.218	0.031			
	MAR	-0.002	0.001		-2.844	0.007			
	SH * Fire type W	-1.015	0.702		-1.445	0.155			
	WS * Fire type W	-0.916	0.708		-1.293	0.202			
ShrubDiv2(S)	Intercept	-7.000	1.025	43.910	0.000	1.000	53	44	0.17
	LogCWD2	4.014	1.026		3.281	0.002			
LowShrub1(S)	Intercept	-1.804	0.591	36.603	-3.051	0.004	53	37	0.31
	TreeStem2	-0.252	0.129		-1.957	0.056			
	MAR	0.002	0.001		3.110	0.003			
LowShrub1(S) (Δ AIC +1.9)	Intercept	-2.287	0.551	39.353	-4.148	<0.001	53	39	0.26
	MAR	0.003	0.001		4.247	<0.001			
LowShrub2(S)	Intercept	0.802	1.052	45.460	0.763	0.449	53	45	0.14
	No. scorched stems	1.039	0.467		2.226	0.030			

Habitat Types		Estimate	SE	Df	t value	P	Null deviance	Residual deviance	R^2
	MAT	-0.090	0.044		-2.048	0.046			
LowShrub3(S)	Intercept	-0.117	0.145	49.275	-0.809	0.422	53	49	0.07
	Fire Type	0.705	0.356		1.983	0.053			

Table 5.5. Generalised Linear Mixed Model output at quadrat level

GLMM fixed effects results for each habitat type (including variance due to site as a random effect and residual variance) at a quadrat level showing the relationship with the strongest environmental or fire history predictor, the adjustment to the intercept for vegetation type or predictor variable, the amount of variation explained by individual quadrats within a site (R^2m) and the variance explained by the total model (R^2c). Fire type W = wildfire; fire type P = prescribed fire; interval (below) = below minimum recommended intervals; interval (within) = within recommended intervals; (above) = above recommended intervals; vegetation types: ST = Southern Tablelands; SH = Sydney Hinterlands; WS = Western Slopes

Habitat types		Estimate	SE	DF	T value	P	R^2m	R^2c
Ground cover								
GndCov1(Q)	Intercept	0.129	0.141	50.254	0.912	0.366	0.186	0.471
(0.291, 0.540)	SH	0.319	0.199	50.254	1.599	0.116		
	WS	-0.726	0.200	50.719	-3.628	<0.001		
GndCov1(Q)	Intercept	-0.152	0.171	100.218	-0.888	0.377	0.198	0.484
(0.294, 0.529)	SH	0.387	0.201	51.585	1.920	0.060		
(Δ AIC +0.1)	WS	-0.728	0.200	50.764	-3.630	<0.001		
	Total volume logs	0.043	0.015	401.084	2.928	<0.001		
GndCov1(Q)	Intercept	-48.129	14.991	51.743	-3.211	0.002	0.087	0.471
(0.393, 0.539)	Longitude	0.321	0.100	51.741	3.210	0.002		
(Δ AIC +11.7)								

Habitat types		Estimate	SE	DF	T value	P	R^2m	R^2c
GndCov2(Q)	Intercept	10.224	3.18	46.849	3.279	0.002	0.227	0.599
(0.387, 0.417)	SH * fire type P	-0.002	0.258	47.259	-0.009	0.993		
	WS * fire type P	-0.268	0.346	46.849	-0.775	0.442		
	ST * fire type W	0.391	0.420	46.866	0.931	0.357		
	Latitude	0.318	0.090	46.760	3.552	<0.001		
	No. logs	0.271	0.125	390.399	2.170	0.031		
	No. tree stems	0.710	0.128	390.333	5.538	<0.001		
	SH * fire type W	-0.526	0.594	46.971	-0.886	0.380		
	WS * fire type W	-1.664	0.597	46.926	-2.789	0.008		
GndCov2(Q)	Interaction	-0.421	0.131	119.840	-3.224	0.002	0.039	0.578
(0.536, 0.420)	No. tree stems	0.711	0.129	390.591	5.523	<0.001		
(Δ AIC +3.7)								
Logs								
Log1(Q)	Intercept	0.256	0.114	51.000	2.236	0.030	0.046	0.175
(0.131, 0.834)	SH	-0.526	0.162	51.000	-3.254	0.002		
	WS	-0.241	0.162	51.000	-1.489	0.143		
Log1(Q)	Intercept	1.520	0.491	51.999	3.098	0.003	0.042	0.172
(0.130, 0.834)	MAT	-0.070	0.022	51.999	-3.126	0.003		
(Δ AIC +0.7)								
Shrub diversity								
LowShrub1(Q)	Intercept	-0.191	0.144	50.240	-1.330	0.189	0.154	0.404
(0.197, 0.779)	SH	0.687	0.200	48.725	3.433	0.001		
	WS	-0.235	0.206	53.661	-1.136	0.261		

Habitat types		Estimate	SE	DF	T value	P	R^2m	R^2c
LowShrub1(Q)	Intercept	-1.813	0.372	52.197	-4.878	<0.001	0.153	0.382
(0.228, 0.614)	MAR	0.002	0.0004	50.625	4.939	<0.001		
(Δ AIC +8.6)								
LowShrub2(Q)	Intercept	-0.592	0.166	266.292	-3.564	<0.001	0.046	0.296
(0.255, 0.607)	No. scorched stems	1.219	0.296	306.446	4.125	<0.001		
LowShrub2(Q)	Intercept	-0.287	0.210	163.541	-1.368	0.173	0.092	0.313
(0.229, 0.479)	SH	-0.461	0.198	46.631	-2.326	0.024		
(Δ AIC +1.3)	WS	-0.350	0.205	51.659	-1.706	0.094		
	No. scorched stems	1.151	0.296	304.830	3.890	<0.001		
LowShrub3(Q)	Intercept	-0.095	0.088	52.258	-1.085	0.283	0.031	0.227
(0.253, 0.712)	Fire type	0.454	0.207	47.571	2.194	0.033		

Table 5.6. Spatial correlations of habitat types among sites

Results of spatial autocorrelation analyses for each principal component and habitat attribute analysed

Habitat	**Observed**	**Expected**	**SD**	***P***
GndCov1	0.178	-0.019	0.069	**0.004**
GndCov2	0.204	-0.019	0.071	**0.002**
LogCWD1	-0.012	-0.019	0.072	0.919
LogCWD2	0.021	-0.019	0.071	0.577
LogHol1	0.226	-0.019	0.072	**<0.001**
TreeHol1	0.210	-0.019	0.072	**0.002**
TreeStem1	0.041	-0.019	0.072	0.406
TreeStem2	0.045	-0.019	0.071	0.367
TreeCan1	0.034	-0.019	0.071	0.459
TreeDiv1	0.055	-0.019	0.072	0.308
TreeDiv2	-0.057	-0.019	0.070	0.586
TreeDiv3	0.099	-0.019	0.072	0.100
ShrubDiv1	0.215	-0.019	0.071	**<0.001**
ShrubDiv2	-0.004	-0.019	0.061	0.813
LowShrub1	0.097	-0.019	0.072	0.107
LowShrub2	-0.058	-0.019	0.071	0.577
LowShrub3	-0.002	-0.019	0.073	0.812
Total volume of logs	0.187	-0.019	0.072	**0.004**
No. scorched logs	0.115	-0.019	0.072	0.062
Log hollows ≥15cm	0.070	-0.019	0.073	0.223
Trees DBH ≥ 60 cm	-0.044	-0.019	0.073	0.732
No. of stems with scorching	0.096	-0.019	0.071	0.105
No. trees with hollows	-0.070	-0.019	0.065	0.429
Tree hollows ≥15cm	-0.040	-0.019	0.073	0.770
No. basal stems	-0.028	-0.019	0.072	0.898

5.5 Discussion

In this study I have used habitat variables measured in the years immediately after a fire but with differing interval to the next fire to investigate the relative influence of vegetation type, fire history, and environmental factors on fauna habitat. Although the three vegetation classes examined here were similar in structure and physiognomy, it was the floristic and fine-scale structural differences in the vegetation types that were the greatest drivers of variation in habitat. Characteristics of the most recent fire and the interval to the next fire did not have as strong an effect on habitat as vegetation type. The fire type (wild versus prescribed) which may be a surrogate for intensity of the most recent fire (Sawyer *et al.* 2018) was one of the best predictors for variation in the landscape for some habitat types.

Understanding how habitat responds to the fire regime at different scales, and whether differences in responses are driven by fire history or environmental factors are critical for effective fire management and planning for biodiversity conservation (Driscoll *et al.* 2010). Methods for defining appropriate fire intervals for ecologically sustainable fire management often involve deriving minimum and maximum intervals based on life history traits of broad plant functional groups (Richardson *et al.* 1994; Kenny *et al.* 2003; Pausas *et al.* 2004; Burrows 2008; van Wilgen *et al.* 2011). Vegetation classification is commonly hierarchical, with broad vegetation groups defined by structure and physiognomy at the top level which can span large areas of varied topography and geology (Groves 1994; Keith 2004). These broad vegetation groups then become the basis for deriving and implementing ecologically sustainable fire intervals for fire management (e.g., South Africa: Kruger *et al.* 2006; NSW: Kenny *et al.* 2003; South Australia: Dept. Environment, Water and Natural Resources 2013; Victoria: Cheal 2010).

Within these broad vegetation groups are types of vegetation defined at a finer scale based largely on floristic composition (Groves 1994; Keith 2004) which may differ in environmental conditions such as soil types, topography, and climate. Vegetation and habitat respond differently to fire spatially and temporally and at different scales (Pastro *et al.* 2013), influenced by fine scale environmental gradients (Davies *et al.* 2012). Managing for fauna at a broad scale considers fauna responses to variation in habitat at a structural level, however as my results demonstrate, fine-scale floristic and structural differences in vegetation account for more of the variation in habitat at a fine scale which may impact fauna survival and recolonisation. For example, *Callitris* species, which are a dominant canopy species in Western Slopes but not Sydney Hinterland or Southern Tableland DSFs, rarely form hollows (Bennett *et al.* 1994) which may account for some of the difference in tree hollow abundance among vegetation types.

Fire alters the structure of vegetation which can impact the suitability of habitat for fauna species (Catling 1991; Fox 1982). Habitat suitability has been linked to time since fire in many ecosystems (Fox 1982; Kelly *et al.* 2011; Watson *et al.* 2012) but can be affected by other elements of the fire regime such as frequency (Collins *et al.* 2012; Aponte *et al.* 2014), intensity (Shive *et al.* 2013), and inter-fire interval (Haslem *et al.* 2012; O'Loughlin *et al.* 2020). In the present study, fire did not have as strong an effect on the variation in habitat as vegetation type. For some habitat types however (see Figures 5.7, 5.8; Figure A4.14), the impacts of fire differ among the vegetation types, demonstrating habitat does not respond uniformly to fire history within a broad vegetation group, which may reduce the suitability of habitat in parts of the landscape for fauna. For example, my results demonstrate that for species requiring large log hollows for survival, areas of Western Slopes DSFS may not be suitable habitat after shorter inter-fire intervals.

Similarly, for species requiring high heterogeneity in the shrub layer, Sydney Hinterlands and Southern Tablelands DSFS may provide less suitable habitat after a prescribed fire.

Whether a fire is wild or prescribed can impact habitat differently and trigger differing post-fire vegetation trajectories (Sah *et al.* 2006). Variable effects on habitat after a wildfire were expected as high severity fires can have lasting impacts on vegetation (Schimmel and Granstrom 1996) and habitat (Collins *et al.* 2012) by simplifying habitat structure (Catling *et al.* 2001) but can also trigger growth resulting in increasing structural complexity in the understorey (Shive *et al.* 2013, present study). Prescribed fires are usually of a lower intensity and patchier than wildfires (Catchpole 2002) which can result in high spatial heterogeneity of the vegetation structure (Fuhlendorf *et al.* 2006). Results of the present study indicate slightly greater structural heterogeneity of the understorey vegetation in areas burnt by wildfire than prescribed fire (see Figure 5.8). However, the effects of fire type in this case may have been muted by a lack of replication of sites where the most recent fire was wild.

The inter-fire interval can have a strong effect on the availability of habitat (Weber and Flannigan 1997; Haslem *et al.* 2012). Too-frequent fire can simplify the vegetation cover and reduce the availability of important habitat attributes (Christensen *et al.* 1981; Fox and Fox 1987; Tasker and Dickman 2004). Elements of the previous fires can influence the post-fire vegetation recovery (Catling 1991; Gill and Catling 2002). In my study, the increased scorching in the below minimum interval sites were one of the few detectable effects of inter-fire interval and may be a legacy of previous fires as well as the most recent fire. With more frequent fire resulting in increased scorching on trees as found here, this may have negative impacts on habitat suitability (Croft *et al.* 2012; Bluff 2016).

Habitat such as tree hollows, fallen logs, dense cover, litter layers and greater structural diversity have been shown to be more abundant in long-unburnt vegetation

(Harmon *et al*. 1986; Kenny *et al*. 2003; Croft *et al.* 2016; Haslem *et al.* 2012), making long-unburnt habitat disproportionately important for some species (Kelly *et al.* 2012; Taylor *et al.* 2012; Nimmo *et al.* 2013). My results suggest that once fire burns a long-unburnt site, the fact that it was long unburnt is less important in determining many habitat attributes than finer-scale floristic and structural features (relating to vegetation type), and climatic differences. For example, differences in shrub and mid-canopy densities between vegetation types appears to be related to differences in species composition rather than the inter-fire interval. The habitat attributes that were more important with a longer inter-fire interval prior to the most recent fire related to the volume and structure of coarse woody debris and the number of large hollows in logs, in keeping with other studies (Harmon *et al*. 1986; Croft *et al.* 2016).

Although the vegetation types used here were chosen to maximise the availability of fire history data, there was insufficient detail to test effects of season, intensity, and interval between successive fires (see Chapter 2.5.1). Yet these are all elements of the fire regime known to strongly influence fauna habitat (e.g., Nappi and Drapeau 2011; Aponte *et al.* 2014; Fairman *et al.* 2016). These factors may account for some of the unexplained variance in my models.

Given the large geographic area of the present study, environmental factors would be expected to be strong drivers of variation in habitat. There are strong relationships between topography, soils, climate, and vegetation structure and species composition (Jones *et al.* 2008; Pausas and Bradstock 2007). Productivity, tree growth (Slatyer and Ferrar 1977; Prior and Bowman 2014), and litter decomposition (Aerts 1997) vary with temperature and rainfall at multiple scales which can influence important habitat features such as ground cover, the abundance of hollow-bearing trees (Bennett *et al.* 1994) and woody debris (Woodall and Liknes 2008, present study). Because climatic gradients are reflected in the inherent differences in composition and structure among the vegetation types, environmental factors and vegetation type often provided equally parsimonious models to predict habitat values. My results indicate while some habitat features (e.g., low (<50 cm) ground cover, shrub cover and logs) are correlated on a larger scale, or driven by environmental gradients, regardless of their vegetation type, for some habitat features a strong localised correlation of values within a fine scale (e.g., habitat attributes used in the ground cover PCs measured in quadrats within a site) account for much of the variation explained by my modelling. These findings highlight the need to consider the impact of local-scale environmental conditions when planning and managing with fire for biodiversity outcomes.

5.6 Conclusions

Understanding the relative influence of fire history and environmental gradients on fauna habitat and the scale at which they operate is critical for conserving biodiversity. My results demonstrate that habitat varied among structurally similar vegetation types, which may be due to differences in floristics and vegetation structure, and environmental conditions linked to location. Characteristics of the most recent fire were not a strong predictor of variation in habitat however, I demonstrate a weaker, but significant effect on fauna habitat of time unburnt prior to a fire and whether the fire is wild or prescribed. I found that the effects of fire may not be predictable as they vary among vegetation types and for my study area of NSW, these effects were at a finer scale than that at which fire management for biodiversity conservation is applied. Ground and low shrub cover, and tree and log hollows showed geographically driven patterns irrespective of vegetation types and fire history, suggesting local environmental factors may have a strong influence on these habitat types.

Chapter 6 General Discussion

Fire has a major influence in the distribution and structure of vegetation in many fire-prone ecosystems across the world. Interactions between climate and environmental conditions lead to varying fire patterns within different ecosystems (French *et al*. 2002; Flannigan *et al.* 2005; Harris *et al.* 2008), which in turn can impact the structure and composition of the vegetation in the landscape (Catling 1991; Gill and Allan 2008).

Fire can impact fauna indirectly through changes to the spatial patterns and structure of vegetation, the composition of plant species, or the availability of resources (Fox 1982; Letnic *et al.* 2004; Sitters *et al*. 2014). These indirect influences of fire on habitat and resources vary at differing spatial (Wan *et al.* 2020) and temporal scales (Watson *et al.* 2012), and the impacts on the structure, and hence suitability of habitat increase in complexity with the overlapping of multiple fires in the landscape (Gill and McCarthy 1998). Therefore, how fire is managed in any given landscape will have large impacts on fauna habitat.

Fire management for biodiversity conservation often involves the derivation of minimum and maximum intervals based on life history traits of broad functional groups of plants (Richardson *et al.* 1994; Kenny *et al.* 2003; Pausas *et al.* 2004; Burrows 2008; van Wilgen *et al.* 2011). However, fire intervals derived from the fire response of plant species can fail to consider important elements such as fire intensity and the legacies of historic fires (Di Stefano *et al*. 2013). The influence of interactions between the historic fire regime and environmental factors on habitat characteristics at multiple scales is poorly understood in many ecosystems (Driscoll *et al.* 2010). Fire regimes are often implemented with the untested assumption that the needs of fauna will be met through plant diversity (Clarke 2008; Driscoll *et al*. 2010). The challenge then for fire management is defining the appropriate fire regime at the appropriate scale that ensures adequate resources for the conservation of both flora and fauna biodiversity.

Fire is applied purposefully to the landscape for the protection of life and property, wildfire management, to conserve biodiversity, and for land management such as agricultural and forestry practices (Whelan 1995; Tran and Wild 2000; Andersen *et al.* 2005; Bartlett *et al*. 2007; Morgan *et al.* 2020). Critical to land management, strategic fire planning, and ecological research are accurate fire histories (Hardy *et al.* 2001; Whelan 2009; Driscoll *et al.* 2010). Fire data are used to allocate resources, forecast fire danger, prepare for wild and prescribed fires (McArthur 1966,1967), and modelling fire behaviour (Bradstock *et al*. 2012). Accurate fire history also underpins critical ecological research to determine the impacts of the various attributes of the fire regime on biodiversity (Morgan *et al.* 2001; Driscoll *et al.* 2010) and thus to determine appropriate inter-fire intervals for biodiversity conservation.

In Australia, fire authorities manage fire at a state and territory level and in the state of NSW there are four main fire agencies responsible for fire management in vegetated areas: the NSW Rural Fire Service (NSW RFS); NSW Fire and Rescue Service; NSW National Parks and Wildlife Service, within NSW Department of Planning, Industry and Environment (DPIE); and the NSW Forestry Corporation. Records of reported incidences of wildfires, prescribed fires or hazard reduction works are stored as GIS spatial records and maintained by the NSW RFS in a central database. There is a facility in this database for records to contain information related to the timing of incidents, the authority responsible, and fire intensity. This central agency is the primary source of fire history for the state, and is used for fire planning and management, as well as for fire research and managing for ecological conservation.

This thesis aimed to provide insights into how the fire history and fire management may interact to affect fauna conservation in south-eastern Australia. I first quantified error in the central database used for fire management and determined the extent to which data quality would impact the planning and management of fire for biodiversity conservation. I then quantified differences in distributions of time since fire among vegetation types, examined if they followed predicted patterns, and looked at the relative correlations of land management actions to distributions of time since fire. This led to the third phase of my research where I investigated the extent to which fire history, vegetation type and environmental factors predict fauna habitat in structurally similar but floristically diverse vegetation types.

6.1 Fire History

Inappropriate fire regimes are a key threat to the habitat and persistence of many species (Evans *et al.* 2011; Woinarski *et al*. 2015; Ward *et al.* 2020) and there is an urgent need to understand the characteristics of the fire regime necessary for animals to persist, to enable effective fire management for the conservation of biodiversity. This requires knowledge of the fire history of the landscape, how fire regimes vary across landscapes, and how species respond to different elements of the fire regime. As such, accurate fire history data are essential to the planning and management of fire.

In Chapter Three of this thesis, I examined the fire history database of NSW and assess how the quality of the stored fire data may affect the interpretation of fire history. In doing so, I identified data quality issues including repeated records due to the merging of multiple data sets, missing records and records missing information important to ecological fire management such as fire intensity and the season of occurrence. I then tested for variation in these over time and among vegetation types, and for differences in error between areas managed for biodiversity conservation and other areas. Data quality issues found in the NSW fire history database are typical of spatial datasets globally (e.g., Egenhofer *et al.* 1994; Goldberg *et al.* 2008).

Each attribute of the fire regime can influence the recovery and structure of vegetation and thereby the suitability of habitat (Abbott 1984; Griffiths and Christian 1996; Coops and Catling 2000; Catling *et al*. 2001; Andersen *et al*. 2005; Watson *et al*. 2012), and knowledge of the history and timing of each attribute is essential for future planning. Information on the severity of historic fires for example, is of particular importance to managing fire for ecological outcomes as the severity of the fire can drive changes in the structure of habitat (Gordon *et al.* 2017), and the severity of the previous fire can influence subsequent fire behaviour (Parks *et al.* 2014; Barker and Price 2018). Increased growth in the understorey triggered by a high-severity fire can result in a subsequent high-severity fire in some ecosystems (Holden *et al.* 2010; van Wagtendonk *et al.* 2012; Barker and Price 2018) and conversely, low-severity fire can result in subsequent low severity fires (Arkle *et al.* 2012). Detectable effects of fire severity may be still evident after multiple successive fires and can lead to changes in the structure and composition of vegetation (Barker *et al.* 2021) and thereby habitat. Fauna have been shown to respond to the post-fire changes in vegetation structure and resources (Monamy and Fox 2000, 2010; Fox *et al.* 2003), and therefore the impacts of not only the most recent fire, but the cumulative impacts of historic fires need to be considered when planning for future fires. This example highlights the potential impacts of fire management for ecological outcomes with unknown long-term fire history and illustrates the need for accurate long-term datasets including information such as the intensity and season of historic fires.

An important finding of my research was that the NSW fire history database was not a comprehensive list of fires; my systematic but not comprehensive search identified many fires not in the database, largely prior to the 1970s (see Chapter 3.3.1.1), but some burnt large areas. This demonstrates that the spatial datasets are not a reliable source for examining long-term trends in fire occurrence in NSW. I also found that these datasets were of limited use for examining aspects of the historic fire regime and the impacts on biodiversity due to the large portion of records missing key details such as a fire date that would indicate season and a measure of intensity. The potential effect of the error in any fire database is misinterpretation of fire trends (Short 2015; Syphard and Keeley 2016) and management decisions being made with unknown levels of uncertainty (Openshaw 1989). Despite the lack of detailed knowledge in the fire history of NSW, land managers are required to make decisions about fire management where the impacts of their decisions on the fire regime could be deleterious to biodiversity if based on incorrect data (Stephens and Ruth 2005). My findings can help to advise land management agencies and database operators of the temporal and spatial constraints of the current fire history records.

The limitations of the NSW fire history database are consistent with other fire databases around the world (Pereira *et al.* 2011; Kraaij *et al.* 2013; Short 2014; Syphard and Keeley 2016). In the present study, the lack of accurate fire history in the NSW database highlights the limited area of NSW with sufficient fire history to conduct detailed research on the impacts of the fire regime on biodiversity, leading to uncertainty in how to interpret the identified changes in fire history over time, and also differences among vegetation types (discussed below).

6.2 Variation in distributions of time since fire among vegetation types

In Chapter Four of this thesis, I used the NSW fire history database to examine the variation among, and predictors of distributions of time since fire for the extant vegetation in NSW. I demonstrated that distributions vary greatly among vegetation types at a landscape scale, but do not follow predicted patterns of longer time between fires in wetter vegetation types. I determined that previous fire history, environmental factors, and land-use were strong predictors of distributions in the landscape. I also showed that distributions are skewed to relatively shorter times since fire than if the full range of times described in the fire management guidelines were being achieved. One possible explanation for this is the possible conflicting pressures for fire agencies to reduce the risk of wildfire through hazard reduction burning whilst also using fire for maintaining ecological outcomes, outlined below.

Prescribed burning is implemented in a range of ecosystems globally (Van Dyke *et al.* 2004; Ascoli *et al.* 2009; Clark *et al.* 2020). Land management agencies use prescribed burning to actively manage fuel loads with the goal of protecting life and property by minimising the severity of wildfires (Fernandes and Botelho 2003; Morgan *et al.* 2020). Prescribed burning is also used to achieve biodiversity conservation goals (Bradstock *et al.* 1995; Richards *et al*. 1999; Haines *et al*. 2001) such as minimising the risk of extinctions (Bradstock *et al*. 1995). In south-eastern Australia, government inquiries into recent large-scale fire events have resulted in calls to increase the amount of hazard reduction burning (Teague *et al.* 2010).

Areas of the landscape that are managed to meet ecological outcomes can have a wide diversity of times since fire. These areas can also have fire applied to contribute towards area burn targets (Office of Environment and Heritage 2013). This can result in conflict between fire intervals required for asset protection and biodiversity conservation. To meet the targets, sometimes these prescribed fires burn large areas of native vegetation (NSW fire history database). This may lead to a skew to shorter intervals, similar to those I have demonstrated in NSW (see Chapter 4.4), because the interval between fires required to reduce fire risk is generally perceived to be shorter (Bradstock *et al.* 1998; Price and Bradstock 2012) than those required for the persistence of biodiversity (e.g., Kenny *et al.* 2003). Too frequent fire can reduce the complexity, availability, and quality of habitat for fauna (Aponte *et al.* 2014; Croft *et al.* 2016).

These land management actions leading to short inter-fire intervals can reduce the amount of mid- to older-age vegetation in the landscape and the key habitat attributes such as tree hollows, fallen logs and dense cover that have been found to be more abundant in long-unburnt vegetation (Harmon *et al.* 1986; Kenny *et al.* 2003; Croft *et al.* 2016). Long-unburnt vegetation has been found to be disproportionately important for some species in different ecosystems (Geerts *et al.* 2012; Di Stefano *et al.* 2013; Kelly *et al.* 2015; Hale *et al.* 2016). However, given the lack of historic fire records and the large areas of extant vegetation in NSW with no fire history records, it is difficult to determine the extent to which the skew to shorter times since fire and the variation among many of the vegetation types in NSW is a result of poor fire history records. Care needs to be taken when interpreting these results as it is likely that large areas of the state with no fire records in the database have a time since fire above the maximum fire intervals.

A key finding of my research reported in Chapter Four was the variation in distributions of time since fire among vegetation types at a local scale. Vegetation classes are a subset within a formation and varied in distributions and were not the same as their overarching formation (see Chapter 4.4.1). Variation in distributions among and within a vegetation formation was expected as fire regimes vary in the landscape due to differences in topography, climate (Beaty *et al.* 2001; Hellberg *et al.* 2004; Flatley *et al.* 2011), soil and geological features (Fensham and Kirkpatrick 1992; Keith 2011) and these factors can interact locally. Fire management for ecological outcomes in NSW is implemented at the level of vegetation formations, which can span large geographical areas (e.g., Dry Sclerophyll Forests (grassy/shrubby sub-formation) which covers 4.9 million hectares of NSW; Table 2.1) with differing topography, geology, and climate. Given the influence of local-scale factors on fire distributions, my results suggest that fire management intervals based on time since fire at a vegetation formation level may be too broad and overlook local-scale differences in effects of fire. Local-scale differences are important because vegetation and thereby habitat can respond differently to fire at multiple scales in the landscape (see Chapter Five) and as such, local-scale factors need to be considered when planning and implementing fire for biodiversity conservation.

6.3 Variation in habitat attributes among structurally similar vegetation types

In Chapter Five of this thesis, I used a field-based study to investigate the impacts of fire history, vegetation type, and environmental factors on habitat attributes, and the extent to which they vary among vegetation types. A lack of adequate fire history for much of NSW meant that sufficient replication of treatments across a large geographic range was only achievable in one vegetation formation in NSW and in three classes within this formation. Part of the grouping of these classes within a formation is broad structural similarity of the dominant plant components. Vegetation classification is often hierarchical, and as in NSW, grouped by common structural and functional features for which fire management for ecological outcomes are applied (e.g., South Africa: Kruger *et al.* 2006; NSW: Kenny *et al.* 2003; South Australia: Department of Environment, Water and Natural Resources 2013; Victoria: Cheal 2010). The findings in this vegetation formation may well be applicable more broadly to vegetation types both within NSW and globally.

My results in Chapter Five show that after a fire, vegetation was a better predictor of the variation in most habitats than was fire history on a site, which could relate to differences in floristics and fine scale structural differences. Although fire did not have as strong an effect as vegetation type, for some habitat types the impacts of fire differed markedly between vegetation types (e.g., logs, log hollows and the heterogeneity of the understorey shrub layer) (see Chapter 5.3.3). However, my study was limited to only a small number of aspects of the fire regime.

The lack of historic fire records for many of the sites in my study meant that I could only determine one inter-fire interval and could only estimate the severity of the most recent fire. Variations in combinations of fire severity and inter-fire intervals impact vegetation structure, composition, and therefore habitat differently (Steel *et al.* 2021). Successive fires at short intervals can result in changes in vegetation composition and condition (Syphard *et al.* 2006; Lippitt *et al.* 2013) modifying fauna habitat (Weber and Flannigan 1997; Haslem *et al.* 2012), fauna species composition (Andersen *et al.* 2005; Smith *et al*. 2013), and persistence (Kiss and Magnin 2006). Long fire intervals can result in changes to the structure and distributions of vegetation (Favier *et al.* 2004) and fauna assemblages (Andersen *et al.* 2006) in the landscape. Therefore, variation in the spatial and temporal arrangement of habitat can arise from the post-fire response of vegetation starting from different baselines in terms of fire history. In this study I demonstrate that some habitat types (e.g., the structure and volume of woody debris and hollows in logs; see Chapter 5.3.3) vary between each inter-fire interval group. However, without knowledge of the intensity and timing of previous fires at each of the sites, I was unable to distinguish to what extent the variation among the vegetation types was attributable to aspects of the historic fire regime beyond those analysed. This further highlights the need for accurate fire history for the planning and implementation of fire for ecological outcomes.

In Chapter Five I demonstrated that habitat varies in the landscape at a local scale, predicted by local-scale environmental factors. I show that key habitat types important for the persistence of fauna in the landscape such as ground cover, woody debris, and tree and log hollows with similar fire histories did not have a uniform response among the vegetation classes (see Chapter 5.3.3). Fire management practices designed for managing plant species survival are based on predictable plant responses to fire at a formation-scale, however my results demonstrate that the response of key fauna habitat attributes is not predictable at this scale and fire management may need to be directed at a finer-scale than that at which they are currently managed.

The post-fire recovery of fine-scale habitat is influenced by local environmental and climatic conditions (Plavsic 2014) which can lead to different rates of recovery within a landscape experiencing the same fire or between fire events (Monamy and Fox 2000). Fauna responses to apparently similar fires have also been shown to vary between locations (Nimmo *et al.* 2014). I was unable to distinguish how much of the variation in habitat between vegetation types was due to the inherent differences in composition and structure between the vegetation types, to fine scale climatic gradients, or to missing historic fire information. However, I was able to demonstrate that each of these factors influence some of the habitat types measured. My results also indicate some habitat features (e.g., low (<50 cm) ground cover, shrub cover and logs) are correlated on a larger scale, or driven by environmental gradients, regardless of their vegetation type. My findings provide further evidence that fire management based on vegetation types grouped by structural similarities may be too broad to capture the subtle variation in habitat attributes among vegetation classes. The impact of local scale environmental gradients needs to be considered when planning and managing fire for ecological outcomes.

Fire management guidelines for appropriate fire regimes to conserve biodiversity are often derived from plant vital attributes (Noble and Slatyer 1980; Kenny *et al.* 2003) however rarely make reference to considerations for fauna (Clarke 2008). Fire intervals derived from the fire response of plant species can result in an uneven distribution of habitat at a local scale, as my findings demonstrate. My work adds to the growing body of work that demonstrates that fire intervals derived based on flora-fire relationships are not necessarily applicable to fauna (e.g., Haslem *et al.* 2012; Di Stefano *et al.* 2013; Hradsky *et al.* 2017; O'Loughlin *et al.* 2020).

6.4 Conclusions

This thesis is an examination of fire history and fire management in the context of fauna conservation in south-eastern Australia. A key finding of my work was that the examined fire history data was less comprehensive than managers assumed. The lack of accurate fire history data for fire attributes critical for biodiversity conservation management (fire frequency, inter-fire interval, season, intensity) results in a limited ability to use the database for the analysis of long-term responses of biota to fire regimes.

A priority for land and fire management agencies must be the improvement of the quality of the fire history currently available and future data collection. A standardised data collection and entry protocol for records into each fire history database would help to eliminate many of the issues of error identified here and elsewhere (San-Miguel-Ayanz *et al*. 2012; Short 2014). Ideally standard protocols should include checks for boundary and attribute accuracy, the recording of the month and year of fire occurrence, type of fire (wild or prescription), and an intensity score. An attribute rating the reliability of each record would allow for evaluation of data accuracy. Additionally, previously recorded fires need to have their data reviewed to update missing attributes that may exist in physical documentation, and unentered fires need to be catalogued to reduce the temporal biases I have identified. Without accurate fire history data, we cannot fully understand pyrodiversity-biodiveristy relationships.

A consequence of the uncertainty of the accuracy of the NSW and other fire history databases around the world (e.g., Africa: Kraaij *et al.* 2013; Belhadj-Khedher *et al.* 2018; North America: Kasischke *et al.* 2002; Short 2014; Syphard and Keeley 2016; Portugal: Pereira *et al.* 2011; Australia: present study) is that fire intervals are derived and implemented in the landscape for biodiversity conservation without a clear understanding of the impacts of each element and the cumulative impacts of the fire regime on fauna. In the present state, any further research to address these issues in NSW will be hampered by large areas of extant vegetation with no fire records. A key step to resolving this issue will be to obtain fire history records from a range of sources including remote sensing imagery, historic maps, newspaper articles, incident reports, and even old documents accumulated in rural fire sheds (e.g., Wittkuhn and Hamilton 2010; Belhadj-Kedher *et al*. 2018) to build a more comprehensive fire database, thereby enabling the identification of areas of long-unburnt vegetation and to quantify fire intervals. Remote sensing can and is being used to retrospectively map fire extent and severity to develop more comprehensive fire history data (e.g., severity and patchiness) and to augment existing fire history databases (McCarthy *et al.* 2017; Gibson *et al.* 2020; Teske *et al.* 2021). It was difficult in distinguish how much of the variation in habitat between vegetation types was due to missing historic fire information (e.g., fire severity) in this study. A more accurate history of fire severity would help to reduce some of the uncertainty.

The second key finding of my work was the variation in distributions of time since fire and fauna habitat attributes at multiple scales in the landscape, driven by vegetation types and local scale environmental and climatic factors. Impacts due to fire history were overwritten by the most recent fire for many of the fauna habitat elements measured. Fire management for ecological outcomes are derived and implemented in the landscape with the assumption that the results from a regional or landscape scale are applicable to the local scale. However, I have demonstrated that key habitat attributes do not respond uniformly to fire history within a broad vegetation group.

The important findings from my thesis that land managers can begin to incorporate into on-ground actions for fire management for biodiversity conservation would be to manage each vegetation class as a separate habitat entity, taking into account fire history and environmental and climatic gradients. Whilst it is not possible to collect fine-scale vegetation structure data across large areas, some on-ground assessment within each planned burn area is required after a wildfire given the large variation in some habitat features when the most recent fire was wild.

In practice, fire management at a finer scale over large areas can be costly, time consuming, and difficult to implement, particularly in the case of vegetation mosaics with differing threshold requirements. Despite these challenges, such fine scale management is imperative for conservation of threatened species and their key habitat attributes, as demonstrated here, and has positive effects on many ecological processes (Bradstock *et al.* 2005). The challenge for scientists and fire managers is to identify a pragmatic balance between the ideal fire regime to conserve biodiversity and what is practically achievable on the ground.

In order to understand the impacts of the various elements of the fire regime in the landscape we need an accurate baseline of habitat attributes from which to assess change.

Given the lack of historic fire data, it is difficult to make inferences about the changes in the availability of habitat attributes with differing spatial and temporal arrangements of fire in the landscape. A useful step to identify the impacts of the various elements of the fire regime and the timing of fires on fauna habitat would be to identify the distribution, abundance, and quality of key habitat attributes in long unburnt vegetation in a range of ecosystems and at a range of times since fire. This would help to quantify the direct impacts of different configurations of the fire regime on habitat and better understand the impacts of shorter fire intervals. This will also help to identify appropriate fire intervals for the persistence of fauna in the landscape and enable predictions of the impacts of future fire scenarios.

References

Abatzoglou JT, Williams AP (2016) Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America* **42**, 11770-11775. doi.org/10.1073/pnas.1607171113

Abbott I (1984) Changes in the abundance and activity of certain soil and litter fauna in the Jarrah forest of Western Australia after a moderate intensity fire. *Soil Research* **22**, 463-469. doi.org/10.1071/SR9840463

Abdelmoty AI, Jones CB (1997) Towards maintaining consistency of spatial databases. In: *Proceedings of the Sixth International Conference on Information and Knowledge Management*. pp.293−200, (ACM Press: New York)

Adams MD, Law BS, French KO (2009) Vegetation structure influences the vertical stratification of open- and edge-space aerial-foraging bats in harvested forests. *Forest Ecology and Management* **258**, 2090-2100. doi.org/10.1016/j.foreco.2009.08.002

Aerts R (1997) Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems: a triangular relationship. *Oikos* **79**, 439-449. doi.org/10.2307/3546886

Agee JK (1996) *Fire ecology of the Pacific Northwest forests*. Island Press, (Washington D.C., USA)

Altangerel K, Kull CA (2013) The prescribed burning debate in Australia: conflicts and compatibilities. *Journal of Environmental Planning and Management* **56**, 103-120. doi.org/10.1080/09640568.2011.652831

Andersen T, Cartensen J, Hernandez-Garcia E, Duarte C.M (2009) Ecological thresholds and regime shifts: approaches to identification. *Trends in Ecology and Evolution* **24**, 49−57. doi: 10.1016/j.tree.2008.07.014

Andersen AN, Cook GD, Corbett LK, Douglas MM, Eager RW, Russell-Smith J, Setterfield SA, Williams RJ, Woinarski CJZ (2005) Fire frequency and biodiversity conservation in Australian tropical savannas: implications from the Kapalga fire experiment. *Australian Journal of Ecology* **30**, 255-263. doi.org/10.1111/j.1442-9993.2005.01441.x

Andersen AN, Hertog T, Woinarski JCZ (2006) Long-term fire exclusion and ant community structure in an Australian tropical savanna: congruence with vegetation succession. *Journal of Biogeography* **33**, 823-832. doi.org/10.1111/j.1365-2699.2006.01463.x

Andersen AN, Parr CL, Lowe LM, Muller WJ (2007) Contrasting fire-related resilience of ecologically dominant ants in tropical savannas of northern Australia. *Diversity and Distributions* **13**, 438-446. doi.org/10.1111/j.1472-4642.2007.00353.x

Andersen AN, Woinarski JCZ and Parr CL (2012) Savanna burning for biodiversity: Fire management for faunal conservation in Australian Tropical savannas. *Austral Ecology* **37**, 658-667. doi.org/10.1111/j.1442-9993.2011.02334.x

Anderson TM, Dempewolf J, Metzger KL, Reed DN, Serneels S (2008) Generation and maintenance of heterogeneity in the Serengeti ecosystem. In: *Serengeti III: Human Impacts on Ecosystem Dynamics* (eds. A.R.E. Sinclair, C. Packer, S.A.R. Mduma, and J.M. Fryxell), pp. 135-182 (University of Chicago Press, Chicago)

Andrew N, Rodgerson L, York A (2000) The use of leaf litter associated with logs as refuges from fire by ants. *Australian Journal of Ecology* **25**, 99-107. doi.org/10.1046/j.1442-9993.2000.01015.x

Angelstam PK (1998). Maintaining and restoring biodiversity in European boreal forests by developing natural disturbance regimes. *Journal of vegetation Science* **9**, 593-602. doi.org/10.2307/3237275

Aponte C, Tolhurst KG, Bennett LT (2014) Repeated prescribed fires decrease stocks and change attributes of coarse woody debris in a temperate eucalypt forest. *Ecological Applications* **24**, 976-989. doi.org/10.1890/13-1426.1

Archibald S, Nickless A, Govender N, Scholes RJ, Lehsten V (2010) Climate and the inter-annual variability of fire in southern Africa: a meta-analysis using long-term field data and satellite-derived burnt area data. *Global Ecology and Biogeography* **19**, 794-809. doi.org/10.1111/j.1466-8238.2010.00568.x

Archibald S, Roy DP, Van Wilgen BW, Scholes RJ (2009) What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology* **15**, 613-630. doi.org/10.1111/j.1365-2486.2008.01754.x

Archibald S, Staver AC, Levin SA (2012) Evolution of human-driven fire regimes in Africa. *Proceedings of the National Academy of Sciences* **109**, 847-852. doi.org/10.1073/pnas.1118648109

Arkle RS, Pilliod DS, Welty JL (2012) Pattern and process of prescribed fires influence effectiveness at reducing wildfire severity in dry coniferous forests. *Forest Ecology and Management* **276**, 174-184. doi.org/10.1016/j.foreco.2012.04.002

Arthur AD, Catling PC, Reid A (2012) Relative influence of habitat structure, species interactions and rainfall on the post-fire population dynamics of ground-dwelling vertebrates. *Austral Ecology* **37**, 958-970. doi.org/10.1111/j.1442-9993.2011.02355.x

Arts DGT, De Keizer NF, Scheffer GJ (2002) Defining and improving data quality in medical registries: a literature review, case study and generic framework. *Journal of the American Medical Informatics Association* **9**, 600−611. doi: 10.1197/jamia.M1087

Ascoli D, Beghin R, Ceccato R, Gorlier A, Lombardi G, Lonati M, Marzano R, Bovio G, Cavallero A (2009) Developing and adaptive management approach to prescribed burning: a long-term heathland conservation experiment in north-west Italy. *International Journal of Wildland Fire* **18**, 737-735. doi.org/10.1071/WF07114

Australian Bureau of Meteorology (2020) 120 years of Australian rainfall. Available from Australian Bureau of Meteorology, Melbourne, Australia, http://www.bom.gov.au/climate/history/rainfall/

Australian Bureau of Meteorology (2021) Climate data online. Available from Australian Bureau of Meteorology, Melbourne, Australia, http://www.bom.gov.au/climate/data/index.shtml?bookmark=200

Australian Bureau of Statistics (2018). Australian Population Grid 2018 in ESRI Grid format. Accessed from:

https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02017-18?OpenDocument

Avitabile SC, Callister KE, Kelly LT, Haslem A, Fraser L, Nimmo DG, Watson SJ, Kenny SA, Taylor RS, Spence-Bailey LM, Bennett AF, Clarke MF (2013) Systematic fire mapping is critical for fire ecology, planning and management: a case study in the semi-arid Murray Mallee, south-eastern Australia. *Landscape and Urban Planning* **117**, 81–91. doi: 10.1016/j.landurbplan.2013.04.017

Bagne KE, Purcell KL (2011) Short-term responses of birds to prescribed fire in fire-suppressed forests of California. *Wildlife Management* **75**, 1051-1060. doi.org/10.1002/jwmg.128

Bai J, Perron P (2003) Computation and analysis of multiple structural change models. *Journal of Applied Econometrics* **18**, 1-22. doi.org/10.1002/jae.659

Baker AG, Catterall C, Benkendorff K, Fensham RJ (2020) Rainforest expansion reduces understorey plant diversity and density in open forest of eastern Australia. *Austral Ecology* **45**, 557-571. doi.org/10.1111/aec.12871

Banks SC, Dujadin M, McBurney L, Blair D, Barker M, Lindenmayer DB (2011) Starting points for small mammal population recovery after wildfire: recolonisation or residual populations? *Oikos* **120**, 26-37. doi.org/10.1111/j.1600-0706.2010.18765.x

Barker JW, Price OF (2018) Positive severity feedback between consecutive fires in dry eucalypt forests of southern Australia. *Ecosphere* **9**, e02110. doi.org/10.1002/ecs2.2110

Barker JW, Price OF, Jenkins ME (2021) Patterns of flammability after a sequence of mixed-severity wildfire in dry eucalypt forests of southern Australia. *Ecosphere* **12**, e03715. doi.org/10.1002/ecs2.3715

Barlow J, Berenguer E, Carmenta R, Franca F (2020) Clarifying Amazonia's burning crisis. *Global Change Biology* **26**, 319-321. doi.org/10.1111/gcb.14872

Barnett JL, How RA, Humphreys WF (1978) The use of habitat components by small mammals in eastern Australia. *Australian Journal of Ecology* **3**, 277-285. doi.org/10.1111/j.1442-9993.1978.tb01177.x

Bartlett T, Leonard M, Morgan G (2007) The mega-fire phenomenon: some Australian perspectives. In: *The 2007 Institute of Foresters of Australia and New Zealand Institute of Forestry Conference Papers*, (Institute of Foresters of Australia, Canberra)

Barton K (2020) MuMIn: Multi-model inference. R Package version 1.43.17. Available from: https://CRAN.R-project.org/package=MuMIn

Bassett M, Chia EK, Leonard SWJ, Nimmo DG, Holland GJ, Ritchie EG, Clarke MF, Bennett AF (2015) The effects of topographic variation and the fire regime on coarse woody debris: insights from a large wildfire. *Forest ecology and Management* **340**, 126-134. doi.org/10.1016/j.foreco.2014.12.028

Bates D, Machler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models using lme4. *Journal of Statistical Software* **67**, 1-48

Batllori E, Parisien MA, Krawchuk MA, Moritz MA (2013) Climate change-induced shifts in fire for Mediterranean ecosystems. *Global Ecology and Biogeography* **22**, 1118-1129. doi.org/10.1111/geb.12065

Beaty RM and Taylor AH (2001) Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California USA. *Journal of Biogeogrpahy* **28**, 955-966. doi.org/10.1046/j.1365-2699.2001.00591.x

Beckage B, Stout IJ (2000) Effects of repeated burning on species richness in a Florida pine savanna: A test of the intermediate disturbance hypothesis. *Journal of Vegetation Science* **11**, 113-122. doi.org/10.2307/3236782

Begg RJ, Martin KC, Price NF (1981) The small mammals of Little Nourlangie Rock N. TV. The effects of fire. *Australian Wildlife Research* **8**, 515-527. doi.org/10.1071/WR9810515

Belhadj-Khedher C, Koutsias N, Karamitsou A, El-Meki T, Ouelhazi B, Hamdi A, Nouri H, Mouillot F (2018) A revised historical fire regime analysis in Tunisia (1985-2010) from a critical analysis of the National Fire Database and Remote Sensing. *Forests* **9**, 59−84. doi: 10.3390/f9020059

Bell DT, Hopkins AJM, Plate JS (1984) Fire in the Kwongan. In: *Kwongan: Plant Life of the Sandplain* (eds. J.S. Plate and J.S. Beard), pp. 178-204 (University of Western Australia Press: Nedlands)

Bennett AF (1993) Microhabitat use by the long-nosed potoroo, *Potorus tridactylus*, and other small mammals in remnant forest vegetation, south-western Victoria. *Wildlife Research* **20**, 267-285. doi.org/10.1071/WR9930267

Bennett AF, Lumsden LF, Nicholls AO (1994) Tree hollows as a resource for wildlife in remnant woodlands: spatial and temporal patterns across the northern plains of Victoria, Australia. *Pacific Conservation Biology* **1**, 222-235. doi.org/10.1071/PC940222

Blaum N, Seymour C, Rossmanith E, Schwager M, Jeltsch F (2009) Changes in arthropod diversity along a land use driven gradient of shrub cover in savanna rangelands: identification of suitable indicators. *Biodiversity and Conservation* **18**, 1187-199. doi.org/10.1007/s10531-008-9498-x

Bluff L (2016) Reducing the effect of planned burns on hollow-bearing trees. Fire and Adaptive Management Report no. 95. Victorian Government Department of Environment, Land, Water and Planning (Melbourne:Victoria)

Bond WJ, Midgley JJ (2001). Ecology of sprouting in woody plants: the persistence niche. *Trends in Ecology and Evolution* **16**, 45-54. doi.org/10.1016/S0169-5347(00)02033-4

Bond WJ, van Wilgen BW (1996) *Fire and Plants*. (Chapman and Hall, London)

Bond WJ, Woodward FI, Midgley GF (2004) The global distribution of ecosystems in a world without fire. *New Phytologist* **165**, 525-538. doi.org/10.1111/j.1469-8137.2004.01252.x

Bonnet X, Lecq S, Lassay JL, Ballouard JM, Barbraud C, Souchet J, Mullin SJ, Provost G (2016) Forest management bolsters native snake populations in urban parks. *Biological Conservation* **193**, 1-8. doi.org/10.1016/j.biocon.2015.11.001

Bowen JB, Pate SJ (1993) The significance of root starch in post-fire shoot recovery of the resprouter *Stirlingia latifolia* R. Br. (Proteaceae). *Annals of Botany* **72**, 7–16. doi.org/10.1006/anbo.1993.1075

Bowman AW, Azzallini A (2018) R package ‘sm’: nonparametric smoothing methods (version 2.2–5.6). http:www.stats.gla.ac.uk/~adrian/sm

Bowman DMJS (1998) Tansley Review No. 101. The impact of Aboriginal landscape burning on the Australian biota. *New Phytologist* **140**, 385-410. doi.org/10.1111/j.1469-8137.1998.00289.x

Bowman DMJS (2000) *Australian Rainforests: Islands of Green in an Ocean of Fire.* (Cambridge University Press: Cambridge)

Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle JC, Harrison SP, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, van der Werf GR, Pyne SJ (2009) Fire in the earth system. *Science* **324**, 481-484. DOI: 10.1126/science.1163886

Bowman DJMS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Mack M, Moritz MZ, Pyne S, Roos CI, Scott AC, Sodhi NS, Swetnam TW (2011) The human dimensions of fire regimes on earth. *Journal of Biogeography* **38**, 2223-2236. doi.org/10.1111/j.1365-2699.2011.02595.x

Bowman DMJS, Perry GL, Higgins SI, Johnson CN, Fuhlendorf SD, Murphy BP (2016) Pyrodiversity is the coupling of biodiversity and fire regimes in food webs. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150169. doi.org/10.1098/rstb.2015.0169

Bowman DMJS, Wood SW, Neyland D, Sanders GJ, Prior LD (2013) Contracting Tasmanian montane grasslands within a forest matrix is consistent with cessation of Aboriginal fire management. *Austral Ecology* **38**, 627-638. doi.org/10.1111/aec.12008

Bradshaw RHW, Tolonen K, Tolonen M (1997). Holocene records of fire from the boreal and temperate zones of Europe. In: *Sediment Records of Biomass Burning and Global Change* (eds. JS Clarke, H Cachier, JG Goldammer, and B Stocks). NATO ASI Series (Series I: Global Environmental Change) vol. 51 (Springer, Berlin, Heidelberg)

Bradstock, R. (1981) Our phoenix flora. *Australian Natural History* **20**, 223-226

Bradstock RA (2010) A biogeographic model of fire regimes in Australia: current and future implications. *Global Ecology and Biogeography* **19**, 145-158. doi.org/10.1111/j.1466-8238.2009.00512.x

Bradstock RA, Bedward M, Gill AM, Cohn, J.S. (2005) Which mosaic? A landscape ecological approach for evaluating interactions between fire regimes, habitats and animals. *Wildlife Research* **32**, 409-423. doi.org/10.1071/WR02114

Bradstock RA, Bedward M, Scott J, Keith DA (1996) Simulation of the effect of spatial and temporal variation in fire regimes on the population viability of a *Banksia* species. *Conservation Biology* **10**, 776-784. doi.org/10.1046/j.1523-1739.1996.10030776.x

Bradstock RA, Cary GJ, Davies I, Lindenmayer DB, Price OF, Williams RJ (2012) Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: Insights from landscape-scale simulation. *Journal of Environmental Management* **105**, 66-75. doi.org/10.1016/j.jenvman.2012.03.050

Bradstock RA, Cohn JS (2002) Fire Regimes and biodiversity in semi-arid mallee ecosystems. In: *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. (eds. R.A. Bradstock, J.E. Williams, and M.A. Gill), pp. 238-258 (Cambridge University Press: Cambridge, UK)

Bradstock RA, Gill AM, Kenny BJ, Scott J (1998). Bushfire risk at the urban interface estimated from historical weather records: consequences for the use of prescribed fire in the Sydney region of south-eastern Australia. *Journal of Environmental Management* **52**, 259-271. doi.org/10.1006/jema.1997.0177

Bradstock RA, Keith DA, Auld TD (1995) Fire and Conservation: imperatives and constraints on managing for diversity. In: *Conserving Biodiversity: Threats and*

Solutions (eds. R.A. Bradstock, T.D. Auld, D.A. Keith, R.T. Kingsford, D. Lunney, and D.P. Sivertsen), pp. 323-334 (Chipping Norton, NSW: Surrey Beatty & Sons)

Bradstock RA, Kenny BJ (2003) An application of plant functional types to fire management in a conservation reserve in southeastern Australia. *Journal of Vegetation Science* **14**, 345-354. doi.org/10.1111/j.1654-1103.2003.tb02160.x

Bradstock RA, Tozer MG, Keith DA (1997) Effects of high frequency fire on floristic composition and abundance in a fire-prone heathland near Sydney. *Australian Journal of Botany* **45**, 641-655. doi.org/10.1071/BT96083

Braithwaite RW (1987) Effects of fire regimes on lizards in the wet-dry tropics of Australia. *Journal of Tropical Ecology* **3**, 265-275

Brando PM, Balch JK, Nepstad DC, Morton DC, Putz FE, Coe MT, Silvero D, Macedo MN, Davidson EA, Nobegra CC, Alencar A, Soares-Filho BS (2014). Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *Proceedings of the National Academy of Science USA*, **111**, 6347-6352. doi.org/10.1073/pnas.1305499111

Brassel K, Bucher F, Stephan E, Vckovski A (1995) Completeness. In: *Elements of spatial data quality* (eds. SC Guptill and JL Morrison), pp. 81−108 (Oxford: Elsevier Science)

Brawn JD, Robinson SK, Thompson III FR (2001) The role of disturbance in the ecology and conservation of birds. *Annual Review of Ecology and Systematics* **32**, 251-276. doi.org/10.1146/annurev.ecolsys.32.081501.114031

Brazma A, Hingamp P, Quackenbush J, Sherlock G, Spellman P, Stoeckert C, Aach J, Ansorge W, Ball C.A, Causton HC, Gaasterland T, Glenisson P, Holstege FCP, Kim IF, Markowitz V, Matese JC, Parkinson H, Robinson A, Sarkans U, Schulze-Kremer S, Stewart J, Taylor R, Vilo J, Vingron M (2001) Minimum information about a microarray experiment (MIAME) - toward standards for microarray data. *Nature Genetics* **29**, 365−371. doi: 10.1038/ng1201-365

Brennan KEC, Christie FJ, York A (2009) Global climate change and litter decomposition: more frequent fire slows decomposition and increases the functional importance of invertebrates. *Global Change Biology* **15**, 2958-2971. doi.org/10.1111/j.1365-2486.2009.02011.x

Brigham RM, Grindal SD, Firman MC, Morissette JL (1997) The influence of structural clutter on activity patterns of insectivorous bats. *Canadian Journal of Zoology* **75**, 131-136. doi.org/10.1139/z97-017

Brockett BH, Biggs HC, van Wilgen BW (2001) A patch mosaic burning system for conservation areas in southern African savannas. *International Journal of Wildland Fire* **10**, 169-183. doi.org/10.1071/WF01024

Brown GW (2001) The influence of habitat disturbance on reptiles in a Box-Ironbark eucalypt forest of south-eastern Australia. *Biodiversity and Conservation* **10**, 161-176. doi.org/10.1023/A:1008919521638

Brown GW, Nelson JL, Cherry KA (1997) The influence of habitat structure on insectivorous bat activity in montane ash forests of the Central Highlands, Victoria. *Australian Forestry* **60**, 138-146. doi.org/10.1080/00049158.1997.10674709

Buckingham S, Murphy N, Gibb H (2019) Effects of fire severity on the composition and functional traits of litter-dwelling macroinvertebrates in a temperate forest. *Forest Ecology and Management* **434**, 279-288. doi.org/10.1016/j.foreco.2018.12.030

Bunnell FL, Houde I (2010) Down wood and biodiversity – implications to forest practices. *Environmental Reviews* **18**, 397-421. doi.org/10.1139/A10-019

Bureau of Meteorology (2020*a*) Major seasonal rainfall zones of Australia map. Available from Australian Bureau of Meteorology, Melbourne, Australia, https://bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=seasgrpb#maps

Bureau of Meteorology (2020*b*) Climate zones based on temperature and humidity map. Available from Australian Bureau of Meteorology, Melbourne, Australia, https://bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=tmp_zones#maps

Bureau of Meteorology (2020*c*) 120 years of Australian rainfall. Available from Australian Bureau of Meteorology, Melbourne, Australia, http://www.bom.gov.au/climate/history/rainfall/

Burrows GE (2002) Epicormic strand structure in *Angophora*, *Eucalyptus* and *Lophostemon (Myrtaceae)* – implications for fire resistance and recovery. *New Phytologist* **153**, 111-131. doi.org/10.1046/j.0028-646X.2001.00299.x

Burrows ND (1985) Reducing the abundance of *Banksia grandis* in the jarrah forest by the controlled use of fire. *Australian Forestry* **48**, 63-70. doi.org/10.1080/00049158.1985.10674424

Burrows ND (2008) Linking fire ecology and fire management in south-west Australian forest landscapes. *Forest Ecology and Management* **255**, 2394-2406. doi.org/10.1016/j.foreco.2008.01.009

Burrows N, Abbott I (2003) Fire in south-west Western Australia: synthesis of current knowledge, management implications and new research direction. In: *Fire in Ecosystems of south-west Western Australia: Impacts and Management* (eds. I. Abbot and N. Burrows), pp. 437-452 (Backhuys Publishers, Leiden)

Burrows N, McCaw L (2013) Prescribed burning in southwestern Australian forests. *Frontiers in Ecology and the Environment* **11**, 25-34. doi.org/10.1890/120356

Burrows ND, Wardell-Johnson G (2003) Fire and plant interactions in forested ecosystems of south-western Australia. In: *Fire in ecosystems of south-western Australia: impacts and management* (eds. I. Abbott and N. Burrows), pp. 225-268 (Backhuys Publishers, Leiden)

Burton PJ, Parisien MA, Hicke JA, Hall RJ, Freeburn JT (2008) Large fires as agents of ecological diversity in the North American boreal forest. *International Journal of Wildland Fire* **17**, 754-767. doi.org/10.1071/WF07149

Campbell AJ, Tanton MT (1981) Effects of fire on the invertebrate fauna of soil and litter in a eucalypt forest. In: *Fire and the Australian Biota* (eds. A. Gill, R. Groves, and I. Noble), pp. 215-241 (Australian Academy of Science, Canberra)

Cardille, JA, Ventura SJ, Turner MG (2001). Environmental and social factors influencing wildfires in the upper Midwest, United States. *Ecological Applications* **11**, 111-127. doi.org/10.1890/1051-0761(2001)011[0111:EASFIW]2.0.CO;2

Carise D, McLellan AT, Carriola J, Love M, Cook T, Bovasso G, Lam V (2001) Suggested specifications for a standardized Addiction Severity Index Database. *Journal of Substance Abuse Treatment* **20**, 239–244. doi: 10.1016/S0740-5472(01)00161-1

Cary GJ, Keane RE, Gardner RH (2006) Comparison of the sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather. *Landscape Ecology* **21**, 121-137. doi.org/10.1007/s10980-005-7302-9

Cary GJ, Morrison DA (1995) Effects of fire frequency on plant species composition of sandstone communities in the Sydney region: combinations of inter-fire intervals. *Australian Journal of Ecology* **20**, 418-426. doi.org/10.1111/j.1442-9993.1995.tb00558.x

Catchpole W (2002) Fire properties and burn patterns in heterogeneous landscapes. In: *Flammable Australia: the fire regimes and biodiversity of a continent* (eds. R.A. Bradstock, J.E. Williams, and A.M. Gill), pp. 199-237 (Cambridge University Press, Cambridge)

Catling PC (1991) Ecological effects of prescribed burning practices on the mammals of southeastern Australia. In: *Conservation of Australia's Forest Fauna* (ed. D. Lunney), pp. 353-363 (The Royal Zoological Society of NSW, Mosman, NSW)

Catling PC, Burt RJ (1995) Studies of the ground-dwelling mammals of eucalypt forests in south-eastern New South Wales: the effect of habitat variables on distribution and abundance. *Wildlife Research* **22**, 271-288. doi.org/10.1071/WR9950271

Catling PC, Burt RJ, Forrester RI (2000) Models of the distribution and abundance of ground-dwelling mammals in the eucalypt forests of north-eastern New South Wales in relation to habitat variables. *Wildlife Research* **27**, 639-654. doi.org/10.1071/WR99066

Catling PC, Coops NC, Burt RJ (2001) The distribution and abundance of ground-dwelling mammals in relation to time since wildfire and vegetation structure in south-eastern Australia. *Wildlife Research* **28**, 555-564. doi.org/10.1071/WR00041

Charron I, Johnson EA (2006). The importance of fires and floods on tree ages along mountainous gravel-bed streams. *Ecological Applications* **16**, 1757-1770. doi.org/10.1890/1051-0761(2006)016[1757:TIOFAF]2.0.CO;2

Chas-Amil ML, Touza J, Garcia-Martinez E (2013) Forest fires in the wildland-urban interface: A spatial analysis of forest fragmentation and human impacts. *Applied Geography* **43**, 127-137. doi.org/10.1016/j.apgeog.2013.06.010

Cheal D (2010) Growth stages and tolerable fire intervals for Victoria's native vegetation data sets. Fire and Adaptive Management Report No. 84. (Department of Sustainability and Environment, East Melbourne, Victoria)

Chia EK, Bassett M, Nimmo DG, Leonard SWJ, Ritchie EG, Clarke MF, Bennett AF (2015) Fire severity and fire-induced landscape heterogeneity affect arboreal mammals in fire-prone forests. *Ecosphere* **6**, 1-14. doi.org/10.1890/ES15-00327.1

Chisholm RA, Wijedasa LS, Swinfield T (2016) The need for long-term remedies for Indonesia's forest fires. *Conservation Biology* **30**, 5-6. doi.org/10.1111/cobi.12662

Christensen PE (1980) The Biology of *Bettongia penicillata* (Gray, 1837) and *Macropus eugenii* (Demarest, 1817) in relation to fire. Forests Department of Western Australia, Bulletin 91 (Perth, WA)

Christensen NL (1993) Fire regimes and ecosystem dynamics. In: *Fire in the Environment: The Ecological, Atmospheric and Climatic Importance of Vegetation Fires* (eds. P.J. Crutzen and J.G. Goldammer), Proceedings of the Dahlem Workshop, 15-20 March 1992, Berlin, pp. 233-244 (Wiley: New York)

Christensen P, Maisey K, Perry DH (1984) Radiotracking the Numbat, *Myrmecobius fasciatus*, in the Perup Forest of Western Australia. *Australian Wildlife Research* **11**, 275-288. doi.org/10.1071/WR9840275

Christensen PE, Recher H, Hoare J (1981) Responses of open forest to fire regimes. In: *Fire and the Australian Biota* (eds. A. Gill, R. Groves, and I. Noble), pp. 367-394 (Australian Academy of Science, Canberra)

Claridge AW, May TW (1994) Mycophagy among Australian mammals. *Australian Journal of Ecology* **19**, 251-275. doi.org/10.1111/j.1442-9993.1994.tb00489.x

Clarke KR and Ainsworth M (1993). A method of linking multivariate community structure to environmental variables. *Marine Ecology-Progress Series* **92**, 205-219

Clarke KR, Gorley RN, Somerfield PJ, Warwick RM (2014). Change in marine communities: an approach to statistical analysis and interpretation. 3rd edition. (PRIMER-E: Plymouth)

Clark MD, Wonkka CL, Kreuter UP, Rogers WE (2020) Interactive effects of prescribed fire and livestock grazing on *Seriphium plumosum* in South African sour bushveld. *African Journal of Range and Forage Science* **37**, 278-285. doi.org/10.2989/10220119.2020.1751287

Clarke M F (2008) Catering for the needs of fauna in fire management: science or just wishful thinking? *Wildlife Research* **35**, 385-394. doi.org/10.1071/WR07137

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

Cohen JD (2000) Preventing disaster – home ignitability in the wildland-urban interface. *Journal of Forestry* **98**, 15-21. doi.org/10.1093/jof/98.3.15

Cochrane MA, Alencar A, Schulze MD, Souza CM, Nepstad DC, Lefebvre P, Davidson EA (1999) Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science* **284**, 1832-1835. doi.org/10.1126/science.284.5421.1832

Collins L, Bradstock RA, Tasker EM, Whelan RJ (2012) Impact of fire regimes, logging and topography on hollows in fallen logs in eucalypt forest of south eastern Australia. *Biological Conservation* **149**, 23-31. doi.org/10.1016/j.biocon.2012.01.065

Coops NC, Catling PC (2000) Estimating forest habitat complexity in relation to time since fire. *Austral Ecology* **25**, 344-351. doi.org/10.1046/j.1442-9993.2000.01045.x

Crimmins MA (2006) Synoptic climatology of extreme fire-weather conditions across the southwest United States. *International Journal of Climatology* **26**, 1001-1016. doi.org/10.1002/joc.1300

Croft P, Hunter JT, Reid N (2016) Forgotten fauna: Habitat attributes of long-unburnt open forests and woodlands dictate a rethink of fire management theory and practice. *Forest Ecology and Management* **366**, 166-174. doi.org/10.1016/j.foreco.2016.02.015

Croft P, Reid N, Hunter JT (2012) The bark of eucalypt trees: habitat quality for arthropods and impact of fire. *Pacific Conservation Biology* **18**, 186-193. doi.org/10.1071/PC130186

Croft P, Reid N, Hunter JT (2010) Experimental burning changes the quality of fallen timber as habitat for vertebrate and invertebrate fauna: implications for fire management. *Wildlife Research* **37**, 574-581. doi.org/10.1071/WR10053

Cueto VR, de Casenave JL (2000) Bird assemblages of protected and exploited coastal woodlands in east-central Argentina. *Wilson Bulletin* **112**, 395-402. doi.org/10.1676/0043-5643(2000)112[0395:BAOPAE]2.0.CO;2

Davies AB, Eggleton P, ven Rensburg BJ, Parr CL (2012) The pyrodiversity-biodiversity hypothesis: a test with savanna termite assemblages. *Journal of Applied Ecology* **49**, 422-430. doi.org/10.1111/j.1365-2664.2012.02107.x

de la Cueva AV, del Barrio JMG, Quero MO, Palomares OS (2006) Recent fire regime in peninsular Spain in relation to forest potential productivity and population density. *International Journal of Wildland Fire* **15**, 397-405. doi.org/10.1071/WF05071

Debus SJS, Ford HA, Tremont SM (2006) Bird communities in remnant woodland on the upper North-west slopes of New South Wales. *Australian Zoologist* **33**, 519-529. doi.org/10.7882/AZ.2006.023

Dellasala DA, Williams JE, Williams CD, Franklin JF (2004). Beyond smoke and mirrors: a synthesis of fire policy and science. *Conservation Biology* **18**, 976-986. doi.org/10.1111/j.1523-1739.2004.00529.x

Department of Agriculture, Water and the Environment (2020). Interim Biogeographic Regionalisation for Australia (Regions – State and Territories) v. 7 (IBRA) [ESRI shapefile]. Accessed from: https://data.gov.au/dataset/interim-biogeographic-regionalisation-for-australia-ibra-version-7-regions

Department of Environment, Water and Natural Resources SA (2013) Ecological Fire Management Guidelines for native vegetation in South Australia, 1st Edition, April 2013. Accessed from: https://environment.sa.gov.au

Department of Planning, Industry and Environment NSW (2017) *Hydrologic Groups of Soils in NSW*. (Department of Planning, Industry and Environment, Parramatta). Accessed from https://datasets.seed.nsw.gov.au/dataset/hydrologic-groups-of-soils-in-nsw7f9e8

Department of Planning, Industry and Environment NSW (2019) *Modified (DEM-S) Elevation Layer*. (Department of Planning, Industry and Environment, Parramatta). Accessed from https://datasets.seed.nsw.gov.au/dataset/modified-digital-elevation-layer

Department of Planning, Industry and Environment (2018) NSW Landuse 2017 v1.2. Accessed from: https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017-v1p2-f0ed

Department of Planning, Industry and Environment NSW (2021) Soil Group (GSG) Soil Type map of NSW – Version 4.5. (Department of Planning, Industry and Environment, Parramatta). Accessed from https://datasets.seed.nsw.gov.au/dataset/great-soil-group-gsg-soil-type-map-of-nsw

DeWilde L, Chapin FS (2006) Human impacts on the fire regime of Interior Alaska: interactions among fuels. ignition sources and fire suppression. *Ecosystems* **9**, 1342-1353. doi.org/10.1007/s10021-006-0095-0

Diaz-Delgado R, Lloret F, Pons X (2004) Spatial patterns of fire occurrence in Catalonia, NE, Spain. *Landscape Ecology* **19**, 731-745. doi.org/10.1023/B:LAND.0000004182.22525. a9

Dillon M, NcNellie M, Oliver I (2010). *Assessing the extent and condition of native vegetation in NSW*. *Monitoring, evaluation and reporting program*. Technical Report Series, (Office of Environment and Heritage: Hurstville, Sydney)

Di Stefano J, McCarthy MA, York A, Duff TJ, Slingo J, Christie F (2013) Defining vegetation age class distributions for multispecies conservation in fire-prone landscapes. *Biological Conservation* **166**, 111-117. doi.org/10.1016/j.biocon.2013.06.022

Di Stefano J, York A, Swan M, Greenfield A, Coulson G (2009) Habitat selection by the swamp wallaby (*Wallabia bicolor*) in relation to diel period, food and shelter. *Austral Ecology* **34**, 143-155. doi:10.1111/j.1442-9993.2008.01890.x

Dimitrakopoulos AP, Vlahou M, Anagnostopoulou Ch G, Mitsopoulos ID (2011) Impact of drought on wildland fires in Greece: implications of climatic change? *Climatic Change* **109**, 331−347. doi: 10.1007/s10584-011-0026-8

Diniz-Filho JA, Bini LM, Hawkins BA (2003) Spatial autocorrelation and red herrings in geographical ecology. *Global Ecology and Biogeography* **12**, 53-64. doi.org/10.1046/j.1466-822X.2003.00322.x

Dowdy AJ (2018). Climatological variability of fire weather in Australia. *Journal of Applied Meteorology and Climatology* **57**, 221-234. doi.org/10.1175/JAMC-D-17-0167.1

Driscoll DA, Henderson MK (2008) How many common reptile species are fire specialists? A replicated natural experiment highlights the predictive weakness of a fire succession model. *Biological Conservation* **141**, 460-471. doi.org/10.1016/j.biocon.2007.10.016

Driscoll DA, Lindenmayer DB, Bennett AF, Bode M, Bradstock RA, Cary GJ, Clarke MF, Dexter N, Fensham R, Friend G, Gill M, James S, Kay G, Keith DA, MacGregor C, Russell-Smith J, Salt D, Watson JEM, Williams RJ, York A (2010) Fire management for biodiversity conservation: Key research questions and our capacity to answer them. *Biological Conservation* **143**, 1928-1939. doi.org/10.1016/j.biocon.2010.05.026

Driscoll DA, Smith AL, Blight S, Maindonald J (2012) Reptile responses to fire and the risk of post-disturbance sampling bias. *Biodiversity and Conservation* **21**, 1607-1625. doi.org/10.1007/s10531-012-0267-5

Duff TJ, Chong DM, Cirulis BA, Walsh SF, Penman TD, Tolhurst KG (2014) Gaining benefits from adversity: the need for systems and frameworks to maximise the data obtained from wildfires. In: *Advances in Forest Fire Research* (ed. DX Viegas), pp. 766−774 (Imprensa da Universidade de Coimbra: Coimbra, Portugal) doi: 10.14195/978-989-26-0884-6_85

Dutta R, Das A, Aryal J (2016). Big data integration shows Australian bush-fire frequency is increasing significantly. *Royal Society Open Science* **3**, 150241. doi.org/10.1098/rsos.150241

Dwire KA, Kauffman JB (2003). Fire and riparian ecosystems in landscapes of the western USA. *Forest Ecology and Management* **178**, 61-74. doi.org/10.1016/S0378-1127(03)00053-7

Dwyer LM, Merriam G (1981) Influence of topographic heterogeneity on deciduous litter decomposition. *Oikos* **37**, 228-237. doi.org/10.2307/3544470

Dwyer E, Pinnock S, Gregoire J-M, Pereira JMC (2000) Global spatial and temporal distribution of vegetation fire as determined from satellite observations. *International Journal of Remote Sensing* **21**, 1289-1302. doi.org/10.1080/014311600210182

Edwards A, Hauser P, Anderson M, McCartney J, Armstrong M, Thackway R, Allan G, Hempel C, Russell-Smith J (2001) A tale of two parks: contemporary fire regimes of Litchfield and Nitmiluk National Parks, monsoonal northern Australia. *International Journal of Wildland Fire* **10**, 79-89. doi.org/10.1071/WF01002

Egenhofer MJ, Clementini E, Di Felice P (1994) Evaluating consistencies among multiple representations. *Proceedings of the Sixth International Symposium on Spatial Data Handling* **2,** 901−920

Ellis RC (1985) The relationship among eucalypt forest, grassland and rainforest in a highland area in north-eastern Tasmania. *Australian Journal of Ecology* **10**, 297-314. doi.org/10.1111/j.1442-9993.1985.tb00891.x

Enright NJ, Fontaine JB, Bowman DMJS, Bradstock RA, Williams RJ (2015) Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment* **13,** 262−272. doi: 10.1890/140231

Enright NJ, Keith DA, Clarke MF, Miller BP (2012) Fire regimes in Australian sclerophyllous shrubby ecosystems: heathlands, heathy woodlands and mallee woodlands. In: *Flammable Australia: Fire regimes, Biodiversity and Ecosystems in* *a Changing World* (eds. R.A. Bradstock, A.M Gill, and R.J. Williams), pp.215-234 (CSIRO Publishing: Melbourne)

Environmental Systems Research Institute (ESRI) (2013) *ArcGIS Release 10.2.1*. Redlands, CA

Evans MC, Watson JEM, Fuller RA, Venter O, Bennett SC, Marsack PR, Possingham HP (2011) The spatial distribution of threats to species in Australia. *Bioscience* **61**, 281-289. doi.org/10.1525/bio.2011.61.4.8

Eyre TJ, Butler DW, Kelly AL, Wang J (2010) Effects of forest management on structural features important for biodiversity in mixed-age hardwood forests in Australia's subtropics. *Forest ecology and Management* **259**, 534-546. doi.org/10.1016/j.foreco.2009.11.010

Fairfax R, Fensham R, Butler D, Quinn K, Sigley B, Holman J (2009) Effects of multiple fires on tree invasion in montane grasslands. *Landscape Ecology* **24**, 1363-1373. doi.org/10.1007/s10980-009-9388-y

Fairman TA, Nitschke CR, Bennett LT (2016) Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. *International Journal of Wildland Fire* **25**, 831-848. doi.org/10.1071/WF15010

Falk DA, Miller C, McKEnzie D, Black AE (2007) Cross-scale analysis of fire regimes. *Ecosystems* **10**, 809-823. doi.org/10.1007/s10021-007-9070-7

Farji-Brener A, Corley JC, Bettinelli J (2002) The effects of fire on ant communities in northwestern Patagonia: the importance of habitat structure and regional context. *Diversity and Distributions* **8**, 235-243. doi.org/10.1046/j.1472-4642.2002.00133.x

Favier C, De Namur C, Dubois MA (2004) Forest progression modes in littoral Congo, Central Atlantic Africa. *Journal of Biogeography* **31**, 1445-1461. doi.org/10.1111/j.1365-2699.2004.01094.x

Fearnhead P, Rigaill G (2019) Changepoint detection in the presence of outliers. *Journal of the American Statistical Association* **114**, 169−183. doi: 10.1080/01621459.2017.1385466

Fensham RJ, Fairfax RJ, Butler DW, Bowman, DMJS (2003) Effects of fire and drought in a tropical eucalypt savanna colonized by rain forest. *Journal of Biogeography* **30**, 1405-1414. doi.org/10.1046/j.1365-2699.2003.00934.x

Fensham RK, Kirkpatrick JB (1992). Soil characteristics and tree species distribution in the Savannah of Melville Island, Northern Territory. *Australian Journal of Botany* **40**, 311-333. doi.org/10.1071/BT9920311

Fernandes PM, Botelho HS (2003) A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* **12**, 117-128. doi.org/10.1071/WF02042

Fernandes PM, Loureiro C, Guiomar N, Pezzatti GB, Manso FT, Lopes L (2014) The dynamics and drivers of fuel and fire in the Portuguese public forest. *Journal of Environmental Management* **146**, 373−382. doi: 10.1016/j.jenvman.2014.07.049

Filkov AI, Duff TJ, Penman TD (2018) Improving fire behaviour data obtained from wildfires. *Forests* **9**, 81−102. doi: 10.3390/f9020081

Firth RSD, Brook BW, Woinarski JCZ, Fordham DA (2010) Decline and likely extinction of a northern Australian native rodent, the Brush-tailed Rabbit -rat *Conilurus penicillatus*. *Biological Conservation* **143**, 1193-1201. doi.org/10.1016/j.biocon.2010.02.027

Fischer J, Lindenmayer DB, Barry S, Flowers E (2005) Lizard distribution patterns in the Tumut fragmentation "Natural Experiment" in south-eastern Australia. *Biological Conservation* **123**, 301-315. doi.org/10.1016/j.biocon.2004.11.018

Fisher DO (2001) Effects of vegetation structure, food and shelter on the home range and habitat use of an endangered wallaby. *Journal of Applied Ecology* **37**, 660-671. doi.org/10.1046/j.1365-2664.2000.00518.x

Fisher DO, Owens IPF (2000) Female home range size and the evolution of social organisation in macropod marsupials. *Journal of Animal Ecology* **69**, 1083-1098. doi.org/10.1111/j.1365-2656.2000.00450.x

Fitzgibbon SI, Wilson RS, Goldizen AW (2010) The behavioural ecology and population dynamics of a cryptic ground-dwelling mammal in an urban Australian landscape. *Austral Ecology* **36**, 722-732. doi.org/10.1111/j.1442-9993.2010.02209.x

Flannigan MD, Cantin AS, de Groot WJ, Wotton M, Newbery A, Gowman LM (2013) Global wildland fire season severity in the 21st century. *Forest Ecology and Management* **294**, 54-61. doi.org/10.1016/j.foreco.2012.10.022

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BL (2005) Future area burned in Canada. *Climatic Change* **72**, 1-16. doi.org/10.1007/s10584-005-5935-y

Flannigan M, Stocks B, Turetsky M, Wotton M (2009) Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology* **15**, 549-560. doi.org/10.1111/j.1365-2486.2008.01660.x

Flatley WT, Lafon CW, Grissino-Mayer HD (2011). Climatic controls on patterns of fire in the southern and central Appalachian Mountains, USA. *Landscape Ecology* **26**, 195-209. doi.org/10.1007/s10980-010-9553-3

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. *Science* **309**, 570-574. DOI: 10.1126/science.1111772

Foley JC (1947) A study of meteorological conditions associated with bush and grass fires and fire protection strategy in Australia. Bulletin 38. (Commonwealth of Australia Bureau of Meteorology)

Fontaine JB, Kennedy PL (2012) Meta-analysis of avian and small-mammal response to fire severity and fire surrogate treatments in US fire-prone forests. *Ecological Applications* **22**, 1547-1561. doi.org/10.1890/12-0009.1

Ford HA, Noske S, Bridges (1986) Foraging of birds in eucalypt woodland in north-eastern New South Wales. *Emu* **86**, 168-179. doi.org/10.1071/MU9860168

Forestry Corporation of NSW (2021). NSW Dedicated State Forests Map. Accessed from: https://data-fcnsw.opendata.arcgis.com/datasets/bbf614f12b58432a85ab680162a0c9e0_0/explore?location=-32.844350%2C148.895100%2C6.77

Fox BJ (1982) Fire and mammalian secondary succession in an Australian coastal heath. *Ecology* **63**, 1332-1341. doi.org/10.2307/1938861

Fox BJ (1990) Changes in the structure of mammal communities over successional time scales. *Oikos* **59**, 321-329. doi.org/10.2307/3545142

Fox MD, Fox BJ (1987) The role of fire in the scleromorphic forests and shrublands of eastern Australia. In: *The Role of Fire in Ecological Systems* (ed. L. Trabaud), pp. 23-48 (SPB Academic Publishing, The Hague)

Fox BJ, McKay GM (1981) Small mammal responses to pyric successional changes in eucalypt forest. *Australian Journal of Ecology* **6**, 29-41. doi.org/10.1111/j.1442-9993.1981.tb01271.x

Fox BJ, Taylor JE, Thompson PT (2003) Experimental manipulation of habitat structure: a retrogression of the small mammal succession. *Journal of Animal Ecology* **72**, 927 – 940. doi: 10.1046/j.1365-2656.2003.00765.x

Fraser BF, Lawson V, Morrison S, Christophersen P, McGreggor S, Rawlinson M (2008) Fire management experiment for the declining Partridge Pigeon, Kakadu National Park. *Ecological Management and Restoration* **4**, 94-102. doi.org/10.1046/j.1442-8903.2003.00142.x

Frazer GW, Canham CD, LErtzman KP (1999) Gap Light Analyzer (GLA): Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation. (Simon Fraser University: British Columbia and the Institute of Ecosystem Studies: New York)

Freedman B, Zelazny V, Beaudette D, Fleming T, Flemming S, Forbes G, Gerrow JS, Johnson G, Woodley S (1996) Biodiversity implications of changes in the quantity of dead organic matter in managed forests. *Environmental Reviews* **4**, 238-265. doi.org/10.1139/a96-013

French NHF, Kasischke ES, Williams DG (2002) Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest. *Journal of Geophysical Research* **108**, 8151. doi.org/10.1029/2001JD000480

Fuhlendorf SD, Harrell WC, Engle DM, Hamilton RG, Davis CA, Leslie DM (2006) Should heterogeneity be the basis for conservation? Grassland bird responses to fire and grazing. *Ecological Applications* **16**, 1706-1716. doi.org/10.1890/1051-0761(2006)016[1706:SHBTBF]2.0.CO;2

Garden JG, McAlpine CA, Possingham HP, Jones DN (2007) Habitat structure is more important than vegetation composition for local-level management of native terrestrial reptile and small mammal species living in urban remnants: A case study from Brisbane, Australia. *Austral Ecology* **32**, 669-685. doi.org/10.1111/j.1442-9993.2007.01750.x

Garvey N, Ben-Ami D, Ramp D, Croft DB (2010) Survival behaviour of swamp wallabies during prescribed burning and wildfire. *Wildlife Research* **37**, 1-12. doi.org/10.1071/WR08029

Geerts S, Malherbe SDT, Pauw A (2012). Reduced flower visitation by nectar-feeding birds in response to fire in Cape fynbos vegetation, South Africa. *Journal of Ornithology* **153**, 297-301

Gibbons P, Lindenmayer DB (1996) Issues associated with the retention of hollow-bearing trees within eucalypt forests managed for wood protection. *Forest Ecology and Management* **86**, 245-279. doi.org/10.1016/0378-1127(95)03692-X

Gibbons P, Lindenmayer D (2002) *Tree Hollows and Wildlife Conservation in Australia*. (CSIRO Publishing, Collingwood: Victoria)

Gibson RK, Bradstock RA, Penman T, Keith DA, Driscoll DA (2015) Climatic, vegetation and edaphic influences on the probability of fire across mediterranean woodlands of south-eastern Australia. *Journal of Biogeography* **42**, 1750-1760. doi.org/10.1111/jbi.12547

Gibson R, Danaher T, Hehir W, Collins L (2020) A remote sensing approach to mapping fire severity in south-eastern Australia using sentinel 2 and random forest. *Remote Sensing of Environment* **240**, 111702. https://doi.org/10.1016/j.rse.2020.111702

Giglio L, Randerson JT, van der Werf GR (2013) Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research: Biogeosciences* **118**, 317−328. doi: 10.1002/jgrg.20042

Gilbert B, Lechowicz MJ (2004) Neutrality, niches, and dispersal in a temperate forest understorey. *PNAS* **101**, 7651-7656. doi.org/10.1073/pnas.0400814101

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

Gill AM (1981) Adaptive responses of Australian vascular plant species to fires. In: *Fire and the Australian Biota* (eds. R.H. Groves and I.R. Noble) pp. 243-272 (Australian Academy of Science, Canberra)

Gill AM (1994) Patterns and processes in open-forests of *Eucalyptus* in southern Australia. In: *Australian Vegetation* (ed. R.H. Groves), pp.197-227 (Cambridge University Press: Cambridge)

Gill AM (1997) *Eucalyptus* and fires: interdependent or independent? In: *Eucalypt Ecology: Individuals to Ecosystems* (eds. J.E. Williams and J.C.Z. Woinarski), pp. 151-167 (Cambridge University Press: Cambridge, UK)

Gill AM, Allen G (2008) Large fires, fire effects and the fire-regime concept. *International Journal of Wildland Fire* **17**, 688-695. doi.org/10.1071/WF07145

Gill AM, Catling PC (2002) Fire regimes and biodiversity of forested landscapes of southern Australia. In: *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World* (eds. R.A. Bradstock, A.M. Gill, and R.J. Williams), pp. 351-372 (CSIRO Publishing, Cambridge, Victoria)

Gill AM, Christian KR, Moore PHR, Forrester RI (1987) Bushfire Incidence, fire hazard and fuel reduction burning. *Australian Journal of Ecology* **12**, 299-306. doi.org/10.1111/j.1442-9993.1987.tb00950.x

Gill AM, Groves RG (1981) Fire regimes in heathlands and their plant ecological effects. In: *Ecosystems of the world 9B: Heathlands and related Shrublands – Analytical Studies* (ed. R.L. Specht), pp. 61-84 (Elsevier Scientific: New York)

Gill AM, McCarthy MA (1998) Intervals between prescribed fires in Australia: what intrinsic variation should apply? *Biological Conservation* **85**, 161-169. doi.org/10.1016/S0006-3207(97)00121-3

Gill AM, Williams JE (1996) Fire regimes and biodiversity: the effects of fragmentation of southeastern Australian eucalypt forests by urbanization, agriculture and pine plantations. *Forest ecology and Management* **85**, 261-278. doi.org/10.1016/S0378-1127(96)03763-2

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. *Geophysical Research Letters* **31**, L18211. doi.org/10.1029/2004GL020876

Gil-Romera G, Carrión JS, Pausas JG, Sevilla-Callejo M, Lamb HF, Fernández S, Burjachs F (2010) Holocene fire activity and vegetation response in South-Eastern Iberia. *Quaternary Science Reviews* **29**, 1082-1092. doi.org/10.1016/j.quascirev.2010.01.006

Goldberg SI, Niemierko A, Turchin A (2008) Analysis of data errors in clinical research databases. *AMIA Annual Symposium Proceedings 6th Nov 2008*, 242-246. doi: europepmc.org/abstract/MED/18998889

Goldingay RL (2009) Characteristics of tree hollows used by Australian birds and bats. *Wildlife Research* **36**, 39-409. doi.org/10.1071/WR08172

Goldingay RL (2012) Characteristics of tree hollows used by Australian arboreal and scansorial mammals. *Australian Journal of Zoology* **59**, 277-294. doi.org/10.1071/ZO11081

Goodchild MF (1995) Attribute Accuracy. In: *Elements of spatial data quality* (eds. S.C. Guptill and J.L. Morrison), pp. 59−80 (Oxford: Elsevier Science)

Gordon CE, Price OF, Tasker EM, Denham AJ (2017) *Acacia* shrubs respond positively to high severity wildfire: Implications for conservation and fuel hazard management. *Science of the Total Environment* **575**, 858-868. oi.org/10.1016/j.scitotenv.2016.09.129

Govender N, Trollope WSW, van Wilgen BW (2006) The effect of fire season, fire frequency, rainfall and management on fire intensity in savanna vegetation in South Africa. *Journal of Applied Ecology* **43**, 748-758. doi.org/10.1111/j.1365-2664.2006.01184.x

Greenberg CH (2001) Response of reptile and amphibian communities to canopy gaps created by wind disturbance in the southern Appalachians. *Forest Ecology and Management* **148**, 135-144. doi.org/10.1016/S0378-1127(00)00486-2

Greenberg CH, Neary DG, Harris LD (1994) Effects of high intensity wildfire and silvicultural treatments on reptile communities in Sand-Pine scrub. *Conservation Biology* **8**, 1047-1057. doi.org/10.1046/j.1523-1739.1994.08041047.x

Greenberg CH, Seiboldt T, Keyser TL, McNab WH, Scott P, Bush J, Moorman CE (2018) Reptile and amphibian response of season of burn in an upland hardwood forest. *Forest Ecology and Management* **409**, 808 – 816. doi: 10.1016/j.foreco.2017.12.016

Greenberg CH, Waldrop TA, Tomcho J, Phillips RJ, Simon D (2013) Bird responses to fire severity and repeated burning in upland hardwood forest. *Forest Ecology and Management* **304**, 80-88. doi.org/10.1016/j.foreco.2013.04.035

Griffiths AD, Christian KA (1996) The effects of fire on the frillneck lizard (*chlamydosaurus kingii*) in northern Australia. *Australian Journal of Ecology* **21**, 386-398. doi.org/10.1111/j.1442-9993.1996.tb00625.x

Groves RH (1994) (ed.). *Australian Vegetation*. 2nd Edition. (Cambridge University Press: UK)

Guedes dos Santos J, Malhado ACM, Ladle RJ, Correia RA, Costa MH (2015) Geographic trends and information deficits in Amazonian conservation research. *Biodiversity Conservation* **24**, 2853−2863. doi: 10.1007/s10531-015-0981-x

Haines TK, Busby RL, Cleaves DA (2001) Prescribed burning patterns in the South: trends, purpose and barriers. *Southern Journal of Applied Forestry* **25**, 149-153. doi.org/10.1093/sjaf/25.4.149

Hale S, Nimmo DG, Cooke R, Holland G, James S, Stevens M, De Bondi N, Woods R, Castle M, Campbell K, Senior K, Cassidy S, Duffy R, Holmes B, White JG (2016). Fire and climatic extremes shape mammal distributions in a fire-prone landscape. *Diversity and Distributions* **22**, 1127-1138. doi.org/10.1111/ddi.12471

Hammill KA, Bradstock RA (2006) Remote sensing of fire severity in the Blue Mountains: influence of vegetation type and inferring fire intensity. *International Journal of Wildland Fire* **15**, 213-226. doi.org/10.1071/WF05051

Hammill KA, Bradstock RA (2009). Spatial patterns of fire behaviour in relation to weather, terrain and vegetation. *Proceedings of the Royal Society of Queensland* **115**, 129-135. doi:epdf/10.3316/ielapa.591528973366972

Hardy CC, Schmidt KM, Menakis JP, Sampson RN (2001) Spatial data for national fire planning and fuel management. *International Journal of Wildland Fire* **10**, 353−372. doi: 10.1071/WF01034

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Andersen NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW (1986) Ecology of coarse woody debris in temperate ecosystems. *Advanced Ecological Resolutions* **15**, 133-302. doi.org/10.1016/S0065-2504(08)60121-X

Harris S, Tapper N, Packham D, Orlove B, Nicholls N (2008) The relationship between the monsoonal summer rain and dry-season fire activity in northern Australia. *International Journal of Wildland Fire* **17**, 674-684. doi.org/10.1071/WF06160

Harwood T (2019). 9s climatology for continental Australia 1976-2005: BIOCLIM variable suite. v1. CSIRO. Data Collection. doi.org/10.25919/5dce30cad79a8

Haslem A, Avitabile SA, Taylor RS, Kelly LT, Watson SJ, Nimmo DG, Kenny SA, Callister KE, Spence-Bailey LM, Bennett AF, Clarke MF (2012) Time-since-fire and inter-fire interval influence hollow availability for fauna in a fire-prone system. *Biological Conservation* **152**, 212−221. doi: 10.1016/j.biocon.2012.04.007

Haslem A., Kelly LT, Nimmo DG, Watson SJ, Kenny SA, Taylor RS, Avitabile SC, Callister KE, Spence-Bailey LM, Clarke MF, Bennett AF (2011) Habitat or fuel? Implications of long-term post-fire dynamics for the development of key resources for fauna and fire. *Journal of Applied Ecology* **48**, 247-256. doi.org/10.1111/j.1365-2664.2010.01906.x

He ZH, Liu XD, Zhao H, Zhou JQ (2013) Forest flammability and temporal and spatial distribution rules of forest fire in Jiangle county of Fuijan province. *Human Agricultural Sciences* **7**, 108-111

Heinselman ML (1981) Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. In: *Proceedings of the Conference, Fire Regimes and Ecosystem Properties, Honolulu, Hawaii, 1978*. USDA Forest Service, General Technical Report WO-26, pp. 7-57 (Washington DC)

Hellberg E, Niklasson M, Ganatrom A (2004). Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. *Canadian Journal of Forestry Research* **34**, 332-338. doi.org/10.1139/x03-175

Henderson M, Kalabokidis K, Marmaras E, Konstantinidis P, Marangudakis M (2005) Fire and Society: A comparative analysis of wildfire in Greece and the United States. *Human Ecology Review* **12**, 169-182. www.jstor.org/stable/24707531

Hernandez M, Stolfo S (1995) The merge/purge problem for large databases. *Proceedings of the 1995 ACM SIGMOD* **24**, 127−138. doi: 10.1145/568271.223807

Hobbs R (2002) Fire regimes and their effects in Australian temperate woodlands. In: *Flammable Australia: the fire regimes and biodiversity of a continent* (eds. R.A. Bradstock, J.E. Williams, and A.M. Gill), pp. 305-326 (Cambridge University Press: Cambridge)

Hobbs RJ, Yates CJ (2003) Impacts of ecosystem fragmentation on plant populations: generalising the idiosyncratic. *Australian Journal of Botany* **51**, 471–488. doi:10.1071/BT03037

Hodgkinson KC (2002) Fire regimes in *Acacia* wooded landscapes: effects on functional processes and biological diversity. In: *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World* (eds. R.A. Bradstock, A.M. Gill, and R.J. Williams), pp. 259-277 (CSIRO Publishing, Cambridge, Victoria)

Holden SR, Gutierrez A, Treseder KK (2013) Changes in soil fungal communities, extracellular enzyme activities, and litter decomposition across a fire chronosequence in Alaskan boreal forests. *Ecosystems* **16**, 34-46. doi.org/10.1007/s10021-012-9594-3

Holden ZA, Jolly WM (2011) Modeling topographic influences on fuel moisture and fire danger in complex terrain to improve wildland fire management decision support. *Forest Ecology and Management* **262**, 2133-2141. doi.org/10.1016/j.foreco.2011.08.002

Holden ZA, Morgan P, Hudak AT (2010) Burn severity of areas reburned by wildfire in the Gila National Forest, New Mexico, USA. *Fire Ecology* **6**, 77-85. doi.org/10.4996/fireecology.0603085

Honeycutt D (2012) Count Overlapping Polygons Tool. Available at: https://blogs.esri.com/esri/arcgis/2012/11/13/spaghetti_and_meatballs/

Hradsky BA, Penman TD, Ababei D, Hanea A, Ritchie EG, York A, Di Stefano J (2017) Bayesian networks elucidate interactions between fire and other drivers of terrestrial fauna distributions. *Ecosphere* **8**, e01926. doi.org/10.1002/ecs2.1926

Hu FS, Higuera PE, Duffy P, Chipman ML, Rocha AV, Young AM, Kelly R, Dietze MC (2015) Arctic tundra fires: natural variability and responses to climate change. *Frontiers in Ecology and the Environment* **13**, 369-377. doi.org/10.1890/150063

Huang F, Liu X-N, Yuan J-G (2000) Study on forest fire danger model with remote sensing based on GIS. *Chinese Geographical Science* **10**, 61-67

Huston M (2003) Understanding the effects of fire and other mortality causing disturbances on species diversity. In: *Fire in Ecosystems of South-West Western Australia: Impacts and Management* (eds. I. Abbott and N. Burrows), pp. 37-70 (Backhuys Publishers, Leiden)

Hutto RL (2008) The ecological importance of severe wildfires: some like it hot. *Ecological Applications* **18**, 1827-1834. doi.org/10.1890/08-0895.1

Hutto RL, Patterson DA (2016) Positive effects of fire on birds may only appear under narrow combinations of fire severity and time-since-fire. *International Journal of Wildland Fire* **25**, 1074-1085. doi.org/10.1071/WF15228

Inions GB, Tanton MT, Davey SM (1989) Effect of fire on the availability of hollows in trees used by the common brushtail possum *Trichosurus vulpeca* Kerr, 1792, and the ringtail possum, *Pseudocheirus peregrinus* Boddaerts, 1785. *Australian Wildlife Research* **16**, 449-458. doi.org/10.1071/WR9890449

James NA, Matteson DS (2014) ecp: An R package for nonparametric multiple change point analysis of multivariate data. *Journal of Statistical Software* **62**, 1-25

Jasinge NU, Huynh T, Lawrie AC (2018) Consequences of season of prescribed burning on two spring-flowering terrestrial orchids and their endophytic fungi. *Australian Journal of Botany* **66**, 298-312. doi.org/10.1071/BT17179

Jayapal R, Qureshi Q, Chellam R (2009) Importance of forest structure versus floristics to composition of avian assemblages in tropical deciduous forests of Central Highlands, India. *Forest Ecology and Management* **257**, 2287-2295. doi.org/10.1016/j.foreco.2009.03.010

Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software* **16**, 309−330. doi: 10.1016/S1364-8152(01)00008-1

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* **6**, 7537. doi.org/10.1038/ncomms8537

Jones MM, Tuomisto H, Borcard D, Legendre P, Clark DB, Olivas PC (2008) Explaining variation in tropical plant community composition: influence of environmental and spatial data quality. *Oecologia* **155**, 593-604. doi.org/10.1007/s00442-007-0923-8

Kainz W (1995) Logical Consistency. In: *Elements of spatial data quality* (eds. S.C. Guptill and J.L. Morrison), pp. 109−138 (Oxford: Elsevier Science)

Kasischke EX, Turetsky MR (2006) Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters* **33**, L09703. doi.org/10.1029/2006GL025677

Kasischke ES, Williams D, Barry D (2002) Analysis of the patterns of large fires in the boreal forest region of Alaska. *International Journal of Wildland Fire* **11**, 131−144. doi: 10.1071/WF02023

Keeley JE (2004) Impact of antecedent climate on fire regimes in coastal California. *International Journal of Wildland Fire* **13**, 173-182. doi.org/10.1071/WF03037

Keeley JE (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* **18**, 116-126. doi.org/10.1071/WF07049

Keeley JE, Fotheringham CJ, Baer-Keeley M (2005) Determinants of postfire recovery and succession in Mediterranean-climate shrublands of California. *Ecological Applications* **15**, 1515-1534. doi.org/10.1890/04-1005

Keeley JE, Fotheringham CJ, Morais M (1999). Reexamining fire suppression impacts on shrubland fire regimes. *Science* **284**, 1829-1832. DOI: 10.1126/science.284.5421.1829

Keeley JE, Pausas JG, Rundel PW, Bond WJ, Bradstock RA (2011) Fire as an evolutionary pressure shaping plant traits. *Trends in Plant Science* **16**, 406-411. doi.org/10.1016/j.tplants.2011.04.002

Keeley JE, Rundel PW (2005) Fire and the Miocene expansion of C-4 grasslands. E*cology Letters* **8**, 683-690. doi.org/10.1111/j.1461-0248.2005.00767.x

Keeley JE, Zedler PH (1978) Reproduction of chaparral shrubs after fire; a comparison of sprouting and seeding species. *American Midland Naturalist* **99**, 142-161. doi.org/10.2307/2424939

Keenan R, Ryan M (2004) Old growth forests in Australia: conservation status and significance for timber product. *Science for Decision Makers* (Bureau of Rural Sciences, Canberra)

Keith DA (2004) *Ocean Shores to Desert Dunes: The Native Vegetation of New South Wales and the ACT*. NSW Department of Environment and Conservation (Hurstville, NSW)

Keith DA (2011). Relationships between geodiversity and vegetation in south-eastern Australia. *Proceedings of the Linnean Society of New South Wales* **132**, 5-26. doi/abs/10.3316/INFORMIT.823833486168280

Keith DA (2012) Functional traits: their roles in understanding and predicting biotic responses to fire regimes from individuals to landscapes. In: *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World* (eds. R.A. Bradstock, A.M. Gill, and R.J. Williams), pp. 97-125 (CSIRO Publishing, Cambridge, Victoria)

Keith DA, McCaw WL, Whelan RJ (2002) Fire regimes in Australian heathlands and their effects on plants and animals. In: *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World* (eds. R.A. Bradstock, A.M. Gill, and R.J. Williams), pp. 199-237 (CSIRO Publishing, Cambridge, Victoria)

Keith DA, Simpson CC (2010) Vegetation formations of NSW (version 3.03): a seamless map for modelling fire spread and behaviour. Report to the Rural Fire Service, NSW Department of Environment and Climate Change (Sydney, NSW)

Kelly LT, Bennett AF, Clarke MF, McCarthy MA (2015) Optimal fire histories for biodiversity conservation. *Conservation Biology* **29**, 473-481. doi.org/10.1111/cobi.12384

Kelly LT, Gilijohann KM, Duane A, Aquilue N, Archibald S, Batllori E, Bennett AF, Buckland ST, Canelles Q, Clarke MF, Fortin MJ, Hermoso V, Herrando S, Keane RE, Lake FK, McCarthy MA, Moran-Ordonez A, Parr CL, Pausas JG, Penman TD, Regos A, Rumpff L, Santos JL, Smith AL, Syphard AD, Tingley MW, Brotons L (2020) Fire and biodiversity in the Anthropocene. *Science* **370**, eabb0355. DOI: 10.1126/science.abb0355

Kelly LT, Nimmo DG, Spence-Bailey LM, Clarke MF, Bennett AF (2010) The short-term responses of small mammals to wildfire in semiarid mallee shrubland, Australia. *Wildlife Research* **37**, 293-300. doi.org/10.1071/WR10016

Kelly LT, Nimmo DG, Spence-Bailey LM, Haslem A, Watson SJ, Clarke MF, Bennett AF (2011) Influence of fire history on small mammal distributions: insights from a 100-year post-fire chronosequence. *Diversity and Distributions* **17**, 462-473. doi.org/10.1111/j.1472-4642.2011.00754.x

Kelly LT, Nimmo DG, Spence-Bailey LM, Taylor RS, Watson SJ, Clarke MF, Bennett AF (2012) Managing fire mosaics for small mammal conservation: a landscape perspective. *Journal of Applied Ecology* **49**, 412-421. doi.org/10.1111/j.1365-2664.2012.02124.x

Kenny B, Sutherland E, Tasker E, Bradstock R (2003) Guidelines for ecologically sustainable fire management. NSW National Parks and Wildlife Service (Hurstville, NSW)

Kipfmueller KF, Baker WL (1998) Fires and dwarf mistletoe in a Rocky Mountain lodge-pole pine ecosystem. *Forest Ecology and Management* **108**, 77-84. doi.org/10.1016/S0378-1127(98)00217-5

Kiss L, Magnin F (2006) High resilience of Mediterranean land snail communities to wildfires. *Biodiversity and Conservation* **15**, 2925-2944. doi.org/10.1007/s10531-005-3430-4

Kitzberger T, Veblen TT, Villalba R (1997). Climatic influences on fire regimes along a rainforest-to-xeric woodland gradient in northern Patagonia, Argentina. *Journal of Biogeography* **24**, 35-47. doi.org/10.1111/j.1365-2699.1997.tb00048.x

Knox KJE, Clarke PJ (2006) Fire season and intensity affect shrub recruitment in temperate sclerophyllous woodlands. *Oecologia* **194**, 730−739. doi: 10.1007/s00442-006-0480-6

Kolanek A, Szymanowski M, Raczyk A (2021) Human activity affects forest fires: the impacts of anthropogenic factors on the density of forest fires in Poland. *Forests* **12**, 728. doi.org/10.3390/f12060728

Koutsias N, Allgower B, Conedera M (2002) What is common in wildland fire occurrence in Greece and Switzerland? – Statistics to study fire occurrence pattern. In: *Proceedings of the 4th international conference on forest fire research, Luso, November 18-23* (ed. DX Viegas), pp. 14 (Millpress Science Publishers Rotterdam, Netherlands)

Kraaij T, Baard JA, Cowling RM, van Wilgen BW, Das S (2013) Historical fire regimes in poorly understood, fire-prone ecosystem: eastern coastal fynbos. *International Journal of Wildland Fire* **22**, 277−287. doi: 10.1071/WF11163

Krawchuk MA, Cumming SG, Flannigan MD (2009) Predicted changes in fire weather suggest increases in lightning fire initiation and future area burned in the mixedwood boreal forest. *Climate Change* **92**, 83-97. doi.org/10.1007/s10584-008-9460-7

Krawchuk MA, Moritz MA (2011) Constraints on global fire activity across a resource gradient. *Ecology* **92**, 121-132. doi.org/10.1890/09-1843.1

Kruger FJ, Forsyth GGG, Kruger LM, Slater K, Le Maitre DC, Matshate J (2006) Classification of veldfire risk in South Africa for the administration of the legislation regarding fire management. In: *Conference Proceedings: 5th International Conference on Forest Fire Research* (ed. DX Viegas), 27-30th November 2006 (Figueira da Foz (Coimbra), Portugal)

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software* **82**, 1-26. doi.org/10.18637/jss.v082.i13

Lamont BB, Pausas JG, He T, Witkowsky ETF, Hanley ME (2020) Fire as a selective agent for both serotiny and nonserotiny over space and time. *Critical Reviews in Plant Sciences* **39**, 140-172. doi.org/10.1080/07352689.2020.1768465

Lassau SA, Hochuli DF (2004) Effects of habitat complexity on ant assemblages. *Ecography* **27**, 157-164. doi.org/10.1111/j.0906-7590.2004.03675.x

Law BS (1993) Roosting and foraging ecology of the Queensland blossom bat (*Syconycteris australis*) in north-eastern New South Wales: flexibility in response to seasonal variation. *Wildlife Research* **20**, 419-431. doi.org/10.1071/WR9930419

Lawes MJ, Murphy BP, Fisher A, Woinarski JC, Edwards AC, Russell-Smith J (2015) Small mammals decline with increasing fire extent in northern Australia: evidence from long-term monitoring in Kakadu National Park. *International Journal of wildland Fire* **24**, 712-722. doi.org/10.1071/WF14163

Lawrence GE, (1966) Ecology of vertebrate animals in relation to chaparral fire in the Sierra Nevada foothills. *Ecology* **4**, 25-45. doi.org/10.2307/1933775

Lawson DM, Regan HM, Zedler PH, Franklin J (2010) Cumulative effects of land use, altered fire regime and climate change on persistence of *Ceanothus verrucosus*, a rare fire-dependent plant species. *Global Change Biology* **16**, 2518-2529. doi.org/10.1111/j.1365-2486.2009.02143.x

Le Mar K, McArthur C (2005) Comparison of habitat selection by two sympatric macropods, *Thylogale billardierii* and *Macropus rufogriseus rufogriseus* in a patchy eucalypt-forestry environment. *Austral Ecology* **30**, 674-683. doi.org/10.1111/j.1442-9993.2005.01510.x

Leahy L, Legge SM, Tuft K, McGregor HW, Barmuta LA, Jones ME, Johnson CN (2016) Amplified predation after fire suppresses rodent populations in Australia's tropical savannas. *Wildlife Research* **42**, 705-716. doi.org/10.1071/WR15011

Legendre P (1993) Spatial autocorrelation: trouble or new paradigm? *Ecology* **74**, 1659-1673. doi.org/10.2307/1939924

Lehmann CER, Archibald SA, Hoffmann, WA, Bond, WJ (2011) Deciphering the distribution of the savanna biome. *New Phytologist* **191**, 197-209. doi.org/10.1111/j.1469-8137.2011.03689.x

Leigh JH (1994) Chenopod shrublands. In: *Australian Vegetation (2nd Edition)*. (ed. R.H. Groves), pp. 345-367 (Cambridge University Press: Cambridge, UK)

Leonard SWJ, Bennett AF, Clarke MF (2014) Determinants of the occurrence of unburnt forest patches: Potential biotic refuges within a large, intense wildfire in south-eastern Australia. *Forest Ecology and Management* **314**, 85-93. doi.org/10.1016/j.foreco.2013.11.036

Lepage Y (1971) Combination of Wilcoxians and Ansari-Bradley Statistics. *Biometrica* **58**, 213-217. doi.org/10.1093/biomet/58.1.213

Letnic M (2003) The effects of experimental patch burning, rainfall on small mammals in the Simpson Desert, Queensland. *Wildlife Research* **30**, 547-563. doi.org/10.1071/WR02093

Letnic M, Dickman CR (2005) The response of small mammals to patches regenerating after fire and rainfall in the Simpson Desert, central Australia. *Austral Ecology* **30**, 24-39. doi.org/10.1111/j.1442-9993.2004.01410.x

Letnic M, Dickman DR (2006). Boom means bust: interactions between the El Nino/Southern Oscillation (ENSO) rainfall and the processes threatening mammal species in arid Australia. *Biodiversity & Conservation* **15**, 3847-3880. doi:10.1007/s10531-005-0601-2

Letnic M, Dickman CR (2010) Resource pulses and mammalian dynamics: conceptual models for hummock grasslands and other Australian desert habitats. *Biological Reviews* **85**, 501-521. doi.org/10.1111/j.1469-185X.2009.00113.x

Letnic M, Dickman CR, Tischler MK, Tanyo B, Beh CL (2004) The responses of small mammals and lizards to post-fire succession and rainfall in arid Australia. *Journal of Arid Environments* **59**, 85-114. doi.org/10.1016/j.jaridenv.2004.01.014

Lindenmayer DB, Franklin JF (2002) *Conserving Forest Biodiversity: A Comprehensive Multiscaled Approach*. (Island Press, Washington)

Lindenmayer DB, Cunningham RB, Tanton MT, Smith AP, Nix HA (1991) Characteristics of hollow-bearing trees occupied by arboreal marsupials in the montane ash forests of the Central Highlands of Victoria, south-east Australia. *Forest Ecology and Management* **40**, 289-308. doi.org/10.1016/0378-1127(91)90047-Y

Lindenmayer DB, Hobbs RJ, Montague-Drake R, Alexandra J, Bennett A, Burgman M, Cale P, Calhoun A, Cramer V, Cullen P, Driscoll D, Fahrig L, Fischer J, Franklin J, Haila Y, Hunter M, Gibbons P, Lake S, Luck G, MacGregor C, McIntyre S, Mac Nally R, Manning A, Miller J, Mooney H, Noss R, Possingham H, Saunders D, Schmiegelow F, Scott M, Simberloff D, Sisk T, Tabor G, Walker B, Wiens J, Woinarski J, Zavaleta E (2008*a*) A checklist for ecological management of landscapes for conservation. *Ecology Letters* **11**, 78-91. doi.org/10.1111/j.1461-0248.2007.01114.x

Lindenmayer DB, Wood JT, Cunningham RB, MacGregor C, Crane M, Michael D, Montague-Drake R, Brown D, Muntz R, Gill AM (2008*c*) Testing hypotheses associated with bird responses to wildfire. *Ecological Applications* **18**, 1967-1983. doi.org/10.1890/07-1943.1

Lindenmayer DB, Wood JT, MacGregor C, Michael DR, Cunningham RB, Crane M, Montague-Drake R, Brown D, Muntz R, Driscoll DA (2008*b*) How predictable are reptile responses to wildfire? *Oikos* **117**, 1086-1097. doi.org/10.1111/j.0030-1299.2008.16683.x

Lippitt CL, Stow DA, O’Leary JF, Franklin J (2013) Influence of short-interval fire occurrence on post-fire recovery pf fire-prone shrublands in California, USA. *International Journal of Wildland Fire* **22**, 184-193. doi.org/10.1071/WF10099

Littell JS, McKEnzie D, Peterson DL, Westerling AL (2009). Climate and wildfire area burned in western US ecoprovinces, 1916-2003. *Ecological Applications* **19**, 1003-1021. doi.org/10.1890/07-1183.1

Liu Y, Stanturf J, Goodrick S (2010) Trends in global wildfire potential in a changing climate. *Forest ecology and Management* **259**, 685-697. doi.org/10.1016/j.foreco.2009.09.002

Liu Z, Yang, J, Chang Y, Weisberg PJ, He HS (2012) Spatial patterns and drivers of fire occurrence and its future trend under climate change in a boreal forest of Northeast China. *Global Change Biology* **18**, 2041-2056. doi.org/10.1111/j.1365-2486.2012.02649.x

Luck GW (2002) The habitat requirements of the rufous treecreeper (*Climacteris rufa*). 1. Preferential habitat use demonstrated at multiple spatial scales. *Biological Conservation* **105**, 383-394. doi.org/10.1016/S0006-3207(01)00222-1

Lumsden LF, Bennett AF, Silins JE (2002) Selection of roost sites by the lesser long-eared bat (*Nyctophilus geoffroyi*) and Gould's wattled bat (*Chalinolobus gouldii*) in south-eastern Australia. *Journal of Zoology* **257**, 207-218. doi.org/10.1017/S095283690200081X

Lunney D, Barker J, Priddel D, O'Connell M (1988) Roost selection by Gould's Long-eared bat *Nyctophilus- Gouli Tomes* (*Chiroptera, Vespertilionidae*), in logged forest on the south coast of New South Wales. *Australian Wildlife Research* **15**, 375-384. doi.org/10.1071/WR9880375

Lunney D, Eby P, O'Connell M (1991) Effects of logging, fire and drought on three species of lizards in Mumbulla State Forest on the south coast of New south Wales. *Australian Journal of Ecology* **16**, 33-46. doi.org/10.1111/j.1442-9993.1991.tb01479.x

Lunt ID (1998) *Allocasuarina* (Casuarinaceae) invasion of an unburnt coastal woodland at Ocean Grove, Victoria: Structural changes 1971-1996. *Australian Journal of Botany* **46**, 649-656. doi.org/10.1071/BT97032

MacArthur RH, MacArthur JW (1961) On bird species diversity. *Ecology* **42**, 594-598. doi.org/10.2307/1932254

MacHunter J, Menkhorst P, Lyon R (2009) Towards a process for integrating vertebrate fauna into fire management planning. Arthur Rylah Institue for Environmental Research Technical Report Series No. 192, Department of Sustainability and Environment (Heidelberg, Victoria)

Mackowski CM (1984) The ontogeny of hollows in Blackbutt, *Eucalyptus pilularis* and its relevance to the management of forests for possums, gliders and timber. In: *Possums and Gliders* (eds. A.P. Smith and I.D. Hume), pp. 517-525 (Surrey Beatty, Sydney NSW)

Main AR (1981) Fire tolerance of heathland animals. In: *Heathlands and Related Shrublands of the World,* vol. 9B, Analytical Studies (ed. R.L. Specht), pp. 85-90 (Elsevier: Amsterdam)

Mac Nally RC (1990) The role of floristics and physiognomy in avian community composition. *Australian Journal of Ecology* **15**, 321-327. doi.org/10.1111/j.1442-9993.1990.tb01036.x

Majer JD, Recher HF, Heterick BE, Postle AC (2001) The canopy, bark, soil and litter invertebrate fauna of the Darling Plateau and adjacent woodland near Perth, Western Australia, with reference to the diversity of forest and woodland invertebrates. *Pacific Conservation Biology* **7**, 229-239. doi.org/10.1071/PC020229

Major RE, Christie FJ, Gowing G (2001) Influence of remnant and landscape attributes on Australian woodland bird communities. *Biological Conservation* **102**, 47-66. doi.org/10.1016/S0006-3207(01)00090-8

Marlon JR, Bartlein PJ, Carcaillet C, Gavin DG, Harrison SP, Higuera PE, Joos F, Power MJ, Prentice IC (2008) Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience* **1**, 697-702. doi.org/10.1038/ngeo313

Masters P (1993) The effects of fire-driven succession and rainfall on small mammals in spinifex grassland at Uluru National Park, Northern Territory. *Wildlife Research* **20**, 808-813. doi.org/10.1071/WR9930803

McArthur AG (1966) Weather and grassland fire behaviour. *Commonwealth Forestry and Timber Bureau Leaflet* **100**, 23 pages.

McArthur AG (1967) Fire behaviour in eucalypt forest. *Commonwealth Forestry and Timber Bureau Leaflet* **107**, 36 pp.

McCarthy MA (2002) Overall Fuel Hazard Guide: Sydney Basin. National Parks and Wildlife Service (Sydney, NSW)

McCarthy MA, Gill AM, Bradstock RA (2001) Theoretical fire-interval distributions. *International Journal of Wildland Fire* **10**, 73-77. doi.org/10.1071/WF01013

McCarthy MA, Gill AM, Lindenmayer DB (1999) Fire regimes in mountain ash forest: evidence from forest age structure, extinction models and wildlife habitat. *Forest Ecology and Management* **124**, 193-203. doi.org/10.1016/S0378-1127(99)00066-3

McCarthy G, Moon K, Smith L (2017) Mapping fire severity and fire extent in forest in Victoria for ecological and fuel outcomes. *Ecological Management and Restoration* **18**, 54-65. https://doi.org/10.1111/emr.12242

McComb W, Lindenmayer D (1999) Dying, dead, and down trees. In: *Maintaining Biodiversity in Forest Ecosystems* (ed. M.L. Hunter), pp. 335-372 (Cambridge University Press: Cambridge)

McElhinny C, Gibbons P, Brack C, Bauhus J (2005) Forest and woodland stand structural complexity Its definition and measurement. *Forest Ecology and Management* **218**, 1-24. doi.org/10.1016/j.foreco.2005.08.034

McElhinny C, Gibbons P, Brack C, Bauhus J (2006) Fauna-habitat relationships: a basis for identifying key stand structural attributes in temperate Australian eucalypt forests and woodlands. *Pacific Conservation Biology* **12**, 89-110. doi.org/10.1071/PC060089

McGregor HW, Legge S, Jones ME, Johnson CN (2016) Extraterritorial hunting expeditions to intense fire scars by feral cats. *Scientific Reports* **6**, 22559. doi.org/10.1038/srep22559

McLoughlin LC (1998) Season of burning in the Sydney region: The historical records compared with recent prescribed burning. *Australian Journal of Ecology* **23**, 393-404. doi.org/10.1111/j.1442-9993.1998.tb00744.x

Mermoz M, Kitzberger T, Veblen TT (2005) Landscape influences on occurrence and spread of wildfires in Patagonian forests and shrubland. *Ecology* **86**, 2705-2715. doi.org/10.1890/04-1850

Merrill DF, Alexander ME (1987) *Glossary of Forest Fire Management Terms*. Fourth Edition. (eds. D.F. Merrill and M.E. Alexander) Publication NRCC No. 26516. National Research Council of Canada, Canadian Committee on Forest Fire management (Ottawa, Ontario)

Meserve PL, Kelt DA, Previtali A, Milstead WB, Gutierrez JR (2011) Global climate change and small mammal populations in north-central Chile. *Journal of Mammalogy* **92**, 1223-1235. doi.org/10.1644/10-MAMM-S-267.1

Meyn A, White PS, Buhk C, Jentsch A (2007) Environmental drivers of large, frequent wildfires: the emerging conceptual model. *Progress in Physical Geography* **31**, 287-312. doi.org/10.1177/0309133307079365

Miller JD, Skinner CN, Safford HD, Knapp EE, Ramirez CM (2012). Trends and causes of severity, size and number of fires in northwestern California USA. *Ecological Applications* **22**, 184-203. doi.org/10.1890/10-2108.1

Miranda BR, Sturtevant BR, Stewart SI, Hammer RB (2011) Spatial and temporal drivers of wildfire occurrence in the context of rural development in northern Wisconsin, USA. *International Journal of Wildland Fire* **21**, 141-154. doi.org/10.1071/WF10133

Mitchell RJ, Liu YQ, O'Brien JJ, Elliot KL, Starr G, Miniat CF, Hiers JK (2014) Future climate and fire interactions in the southeastern region of the United States. *Forest Ecology and Management* **327**, 316-326. doi:10.1016/j.foreco.2013.12.003

Mitchener L, Parker A (2005) Climate, lightning and wildfire in the national forests of the southeastern United States: 1989-1998. *Physical Geography* **26**, 147-162. doi.org/10.2747/0272-3646.26.2.147

Mollicone D, Eva H, Achard F (2006) Human role in Russian wild fires. *Nature* **440**, 436-437. doi.org/10.1038/440436a

Monamy V, Fox BJ (2000) Small mammal succession is determined by vegetation density rather than time elapsed since disturbance. *Austral Ecology* **25**, 580-587. doi.org/10.1111/j.1442-9993.2000.tb00063.x

Monamy V, Fox BJ (2010) Responses of two species of heathland rodents to habitat manipulation: vegetation density thresholds and the habitat accommodation model. *Austral Ecology* **35**, 334-347. doi.org/10.1111/j.1442-9993.2009.02042.x

Moreria F, Rego FC, Ferreira PG (2001) Temporal (1958-1995) pattern of change in a cultural landscape of northwestern Portugal: implications of fire occurrence. *Landscape Ecology* **16**, 557-567. doi.org/10.1023/A:1013130528470

Moreno MV, Conedera M, Chuvieco E, Pezzatti GB (2014) Fire regime changes and major driving forces in Spain from 1968 to 2010. *Environmental Science and Policy* **37**, 11−22. doi: 10.1016/j.envsci.2013.08.005

Morgan GW, Tolhurst KG, Poynter MW, Cooper N, McGuffog T, Ryan R, Wouters MA, Stephens N, Black P, Sheehan D, Leeson P, Whight S, Davey SM (2020) Prescribed burning in south-eastern Australia: history and future directions. *Australian Forestry* **83**, 4-28. doi.org/10.1080/00049158.2020.1739883

Morgan P, Hardy CC, Swetnam TW, Rollins MG, Long DG (2001) Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. *International Journal of Wildland Fire* **10**, 329-342. doi.org/10.1071/WF01032

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 fire. *Nature* **515**, 58-66. doi.org/10.1038/nature13946

Moritz MA, Parisien MA, Batllori E, Krawchuck MA, Van Dorn J, Ganz DJ, Hayhoe K (2012) Climate change and disruptions to global fire activity. *Ecosphere* **3**, 1-22. doi.org/10.1890/ES11-00345.1

Morrison DA, Buckney RT, Bewick BJ, Cary GJ (1996) Conservation conflicts over burning bush in south-eastern Australia. *Biological Conservation* **76**, 167-175. doi.org/10.1016/0006-3207(95)00098-4

Morrison DA, Cary GJ, Pengelly SM, Ross DG, Mullins BJ, Thomas CR, Anderson, TS (1995) Effects of fire frequency on plant species composition of sandstone communities in the Sydney region: inter-fire interval and time-since-fire. *Austral Ecology* **20**, 239-247. doi.org/10.1111/j.1442-9993.1995.tb00535.x

Mouillot F, Ratte JP, Joffre R, Moreno JM, Rambal S (2003) Some determinants of the spatio-temporal fire cycle in a Mediterranean landscape (Corsica, France). *Landscape Ecology* **18**, 665-674. doi.org/10.1023/B:LAND.0000004182.22525.a9

Mowat EJ, Webb JK, Crowther MS (2014) Fire-mediated niche separation between two sympatric small mammal species. *Austral Ecology* **40**, 50-59. doi.org/10.1111/aec.12166

Munks SA, Corkrey R, Foley WJ (1996) Characteristics of arboreal marsupial habitat in the semi-arid woodlands of northern Queensland. *Wildlife Research* **23**, 185-195. doi.org/10.1071/WR9960185

Murphy BP, Bradstock RA, Boer MM, Carter JC, Cary GJ, Cochrane MA, Fensham RJ, Russell-Smith J, Williamson GJ, Bowman DMJS (2013) Fire regimes of Australia: a pyrogoegraphic model system. *Journal of Biogeography* **40**, 1048-1058. doi.org/10.1111/jbi.12065

Murphy BP, Cochrane MA, Russell-Smith J (2015) Prescribed burning protects endangered tropical heathlands of the Arnhem Plateau, northern Australia. *Journal of Applied Ecology* **52**, 980-991. doi.org/10.1111/1365-2664.12455

Murphy SA, Legge SM, Heathcote J, Mulder E (2010) The effects of early and late-season fires on mortality, dispersal, physiology and breeding of red-backed fairy-wrens (*Malurus melanocephalus*). *Wildlife Research* **37**, 145−155. doi: 10.1071/WR09007

Nano CEM, Clarke PJ, Pavey CR (2012) Fire regimes in arid hummock grasslands and Acacia shrublands. In: *Flammable Australia: the fire regimes and biodiversity of a continent* (eds. R.A. Bradstock, J.E. Williams, and A.M. Gill), pp. 195−214 (Cambridge University Press: Cambridge, UK)

Nappi A, Drapeau P (2011) Pre-fire forest conditions and fire severity as determinants of the quality of burned forests for deadwood dependent species: the case of the black-backed woodpecker. *Canadian Journal of Forest Research* **41**, 994-1003. doi.org/10.1139/x11-028

New South Wales Environmental Protection Agency (2018). NSW State of the Environment Report 2018. Accessed from: https://www.soe.epa.nsw.gov.au/all-themes/land/native-vegetation

New South Wales Government (2021). NSW Transport Theme - Classified Fire Trail GIS Layer. Accessed from: https://portal.spatial.nsw.gov.au/server/rest/services/NSW_Transport_Theme/FeatureServer/9

New South Wales Government (2021). NSW Transport Theme – Road Segment GIS Layer. Accessed from: https://portal.spatial.nsw.gov.au/server/rest/services/NSW_Transport_Theme/FeatureServer/5

New South Wales Rural Fire Service (2021) Bush Fire Environmental Assessment Code. (NSW Rural Fire Service, Sydney NSW)

Newsome AE, McIlroy J, Catling PC (1975) The effects of an extensive wildfire on populations of twenty ground vertebrates in south-east Australia. *Proceedings of the Ecological Society of Australia* **9**, 107-123

Newsome AE, Catling PC (1983) Animal demography in relation to fire and shortage of food: some indicative models. In: *Mediterranean-Type Ecosystems: The Role of Nutrients* (eds. F.J. Kruger, D.T. Mitchell, and J.U.M. Jarvis), pp. 490-505 (Springer-Verlag, Berlin)

Nichols OG, Bamford MJ (1985) Reptile and frog utilisation of rehabilitated bauxite minesites and dieback-affected sites in Western Australia's Jarrah *Eucalyptus marginate* forest. *Biological Conservation* **34**, 227-249. doi.org/10.1016/0006-3207(85)90094-1

Nicholson PH (1981) Fire and the Australian Aborigine – an enigma. In: *Fire and the Australian Biota* (eds. A.M. Gill, R.H. Groves, and I.R. Noble), pp. 55-76 (Australian Academy of Science, Canberra)

Niklasson M, Granstrom A (2000) Number and size of fires: long-term spatially explicit fire history in a Swedish boreal landscape. *Ecology* **81**, 1484-1499. doi.org/10.1890/0012-9658(2000)081[1484:NASOFL]2.0.CO;2

Nimmo DG, Kelly LT, Farnsworth LM, Watson SJ, Bennett AF (2014) Why do some species have geographically varying responses to fire history? *Ecography* **37**, 805-813. doi.org/10.1111/ecog.00684

Nimmo DG, Kelly LT, Spence-Bailey LM, Watson SJ, Taylor RS, Clarke MF, Bennett AF (2013) Fire mosaics and reptile conservation in a fire-prone region. *Conservation Biology* **27**: 345-353. doi.org/10.1111/j.1523-1739.2012.01958.x

Noble IR, Slatyer RO (1980) The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. *Vegetatio* **43**, 5-21. doi.org/10.1007/BF00121013

Noske RA (1985) Habitat use by three bark foragers of eucalypt forests. In: *Birds of Eucalypt Forests and Woodlands: Ecology, Conservation, Management*. (eds. A Keast, HF Recher, H Ford, D Saunders) pp. 193-204. (Surrey Beaty and Sons: Chipping Norton)

O’Donnell KM, Thompson FR, Semlitsch RD (2016) Prescribed fire alters surface activity and movement behaviour of a terrestrial salamander. *Journal of Zoology* **298**, 303-309. doi.org/10.1111/jzo.12316

O’Loughlin C, Courtney Jones S, Jenkins M, Gordon CE (2020) The effects of inter-fire interval on flora-fauna interactions in a sub-alpine landscape. *Forest Ecology and Management* **473**, 118316. doi.org/10.1016/j.foreco.2020.118316

Office of Environment and Heritage (2013) *Living with fire in NSW National Parks.* (Office of Environment and Heritage, NSW)

Ogden J, Basher L, McGlone MS (1998) Fire, forest regeneration and links with early human habitation: evidence from New Zealand. *Annals of Botany* **81**, 687-696. doi.org/10.1006/anbo.1998.0637

Oh KJ, Roh TH, Moon MS (2005) Developing time-based clustering neural networks to use change-point detection: Application to financial time series. *Asia-Pacific Journal of Operational Research* **22**, 51−70. doi: 10.1142/S0217595905000431

Oliver I, Mac Nally R, York A (2000) Identifying performance indicators of the effects of forest management on ground-active arthropod biodiversity using hierarchical partitioning and partial canonical correspondence analysis. *Forest ecology and Management* **139**, 21-40. doi.org/10.1016/S0378-1127(99)00343-6

Olson DL, Agee JK (2005). Historical fires in Douglas-fir dominated riparian forests of the southern Cascades, Oregon. *Fire Ecology* **1**, 50-74. doi.org/10.4996/fireecology.0101050

Ooi MKJ, Ault TD, Whelan RJ (2004) Delayed post-fire seedling emergence linked to season: a case study with *Leucopogon* species (Epacridaceae). *Plant Ecology* **174**, 183-196. doi:10.1023/B:VEGE.0000046171.97671.e6

Openshaw S (1989) Learning to live with errors in spatial databases. In: *Accuracy of spatial Databases* (eds. M. Goodchild and S. Goopal), pp. 263−276 (Taylor and Francis: London, UK)

Padilla M, Stehman SV, Ramo R, Corti D, Hantson S, Oliva P, Alonso-Canas I, Bradley AV, Tansey K, Mota B, Pereira JM, Chuvieco E (2015). Comparing the accuracies on remote sensing global burned area products using stratified random sampling and estimation. *Remote Sensing of Environment* **160**, 114-121. doi.org/10.1016/j.rse.2015.01.005

Page ES (1955) A test for change in a parameter occurring at an unknown point. *Biometrika* **42**, 523-537. doi: 10.2307/2333401

Palmquist KA, Peet RK, Weakley AS (2014) Changes in plant species richness following reduced fire frequency and drought in one of the most species-rich savannas in North America. *Journal of Vegetation Science* **25**, 1426-1437. doi.org/10.1111/jvs.12186

Panzer R (2003). Importance of in situ survival, recolonization and habitat gaps in the postfire recovery of fire-sensitive prairie insect species. *Natural Areas Journal* **23**, 14-21. www.jstor.org/stable/43912095

Paradis E, Schliep K (2019) ape 5.0: an environment for modern phylogenetics and evolutionary analysis in R. *Bioinformatics* **35**, 526-528. doi.org/10.1093/bioinformatics/bty633

Paritsis J, Veblen TT, Holz A (2015). Positive fire feedbacks contribute to shifts from *Nothofagus pumilio* forests to fire-prone shrublands in Patagonia. *Journal of Vegetation Science* **26**, 89-101. doi.org/10.1111/jvs.12225

Parks SA, Miller C, Nelson CR, Holden ZA (2014) Previous fires moderate burn severity of subsequent wildfires in two large western US wilderness areas. *Ecosystems* **17**, 29-42. doi.org/10.1007/s10021-013-9704-x

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

Parr CL, Brockett BH (1999) Patch-mosaic burning: a new paradigm for savanna fire management in protected areas? *Koedoe* **42**, 117-130. doi.org/10.4102/koedoe.v42i2.237

Parr CL, Robertson HG, Biggs HC, Chown SL (2004) Response of African savanna ants to long-term fire regimes. *Journal of Applied Ecology* **41**, 630-642. doi.org/10.1111/j.0021-8901.2004.00920.x

Pastro LA, Dickman CR, Letnic M (2011) Burning for biodiversity or burning biodiversity? Prescribed burn vs. wildfire impacts on plants, lizards and mammals. *Ecological Applications* **21**, 3238-3253. doi.org/10.1890/10-2351.1

Pastro LA, Dickman CR, Letnic M (2013) Effects of wildfire, rainfall and region on desert lizard assemblages: the importance of multi-scale processes. *Oecologia* **173**, 603-614. DOI:10.1007/s00442-013-2642-7

Pausas JG (1999) Mediterranean vegetation dynamics: modelling problems and functional types. *Plant Ecology* **140**, 27-39. doi.org/10.1023/A:1009752403216

Pausas JG (2009) Response of plant functional types to changes in a fire regime in Mediterranean ecosystems: A simulation approach. *Journal of Vegetation Science* **10**, 717-722. doi.org/10.2307/3237086

Pausas JG, Bradstock RA (2007) Fire persistence traits of plants along a productivity and disturbance gradient in mediterranean shrublands of south-east Australia. *Global Ecology and Biogeography* **16**, 330-340. doi.org/10.1111/j.1466-8238.2006.00283.x

Pausas JG, Bradstock RA, Keith DA, Keeley JE, Network GF (2004) Plant functional traits in relation to fire in crown-fire ecosystems. *Ecology* **85**, 1085-1100. doi.org/10.1890/02-4094

Pausas JG, Braithwaite LW, Austin MP (1995) Modelling habitat quality for arboreal marsupials in the South Coastal forests of New South Wales, Australia. *Forest ecology and Management* **78**, 39-49. doi.org/10.1016/0378-1127(95)03598-5

Pausas JG, Keeley JE (2014) Evolutionary ecology of resprouting and seeding in fire-prone ecosystems. *New Phytologist* **204**, 55-65. doi:10.1111/NPH.12921

Pearce J (1996) Habitat selection by the White-eared Honeyeater. II. A case study at Yellingbo State Nature Reserve, south-east Victoria. *Emu* **96**, 50-54. doi.org/10.1071/MU9960050

Penman TD, Christie FJ, Andersen AN, Bradstock RA, Cary GJ, Henderson MK, Price O, Tran C, Wardle GM, Williams RJ, York A. (2011) Prescribed burning: how can it work to conserve the things we value? *International Journal of Wildland Fire* **20**, 721-733. doi.org/10.1071/WF09131

Penman TD, Kavanagh RP, Binns DL, Melick DR (2007) Patchiness of prescribed burns in dry sclerophyll eucalypt forests in South-eastern Australia. *Forest Ecology and Management* **252**, 24-32. doi.org/10.1016/j.foreco.2007.06.004

Pereira MG, Malamud BD, Trigo RM, Alves PI (2011) The history and characteristics of the 1980-2005 Portuguese rural fire database. *Natural Hazards and Earth System Sciences* **11**, 3343−3358. doi: 10.5194/nhess-11-3343-2011

Peterson DW, Reich PB (2001) Prescribed fire on oak savanna: fire frequency effects on stand structure and dynamics. *Ecological Applications* **11**, 914-927. doi.org/10.1890/1051-0761(2001)011[0914:PFIOSF]2.0.CO;2

Pew KL, Larsen CPS (2001). GIS analysis of spatial and temporal patterns of human-caused wildfires in the temperate rain forest of Vancouver Island, Canada. *Forest Ecology and Management* **140**, 1-18. doi.org/10.1016/S0378-1127(00)00271-1

Pezzatti GB, Zumbrunnen T, Burgi M, Ambrosetti P, Conedera M (2013) Fire regime shifts as a consequence of fire policy and socio-economic development: An analysis based on the change point approach. *Forest Policy and Economics* **29**, 7−18. doi: 10.1016/j.forpol.2011.07.002

Pike DA, Webb JK, Shine R (2011) Chainsawing for conservation: Ecologically informed tree removal for habitat management. *Ecological Management & Restoration* **12**, 110-118. doi.org/10.1111/j.1442-8903.2011.00582.x

Pivello VR (2011) The use of fire in the Cerrado and Amazonian rainforests of Brazil: past and present. *Fire Ecology* **7**, 24-39. doi.org/10.4996/fireecology.0701024

Plasvic MJ (2014) Proximate and ultimate drivers of small-mammal recolonization after fire: microhabitat conditions, rainfall and species traits. *Animal Conservation* **17**, 573-582. doi.org/10.1111/acv.12124

Pohlert T (2018) trend: Non-parametric trend tests and change-point detection. R package version 1.1.0. https://CRAN.R-project.org/package=trend

Price OF, Bradstock RA (2011) Quantifying the influence of fuel age and weather on the annual extent of unplanned fires in the Sydney region of Australia. *International Journal of Wildland Fire* **20**, 142-151. doi.org/10.1071/WF10016

Price OF, Bradstock RA (2012) The efficacy of fuel treatment in mitigating property loss during wildfires: Insights from analysis of the severity of the catastrophic fires in

2009 in Victoria, Australia. *Journal of Environmental Management* **113**, 146-157. doi.org/10.1016/j.jenvman.2012.08.041

Price OF, Russell-Smith J, Edwards A (2003) Fine-scale patchiness of different fire intensities in sandstone heath vegetation in northern Australia. *International Journal of Wildland Fire* **12**, 227-236. doi.org/10.1071/WF03040

Prior LD, Bowman DMJS (2014) Big eucalypts frow more slowly in a warm climate: evidence of an interaction between tree size and temperature. *Global Change Biology* **20**, 2793-2799. doi.org/10.1111/gcb.12540

R Core Team (2018) R: A language and environment for statistical computing. (R Foundation for Statistical Computing: Vienna, Austria). URL: https://www.R-project.org/

R Core Team (2020). R: A language and environment for statistical computing. (R Foundation for Statistical Computing: Vienna, Austria). URL: https://www.R-project.org/

R Core Team (2021). R: A language and environment for statistical computing. (R Foundation for Statistical Computing: Vienna, Austria). URL: https://www.R-project.org/

Radford IJ, Woolley LA, Corey B, Vigilante T, Wunambal Gaambera Aboriginal Corporation, Hatherley E, Fairman R, Carnes K, Start AN (2020) Prescribed burning benefits threatened mammals in northern Australia. *Biodiversity and Conservation* **29**, 2985-3007. doi.org/10.1007/s10531-020-02010-9

Rainho A, Augusto AM, Palmeirim JM (2010) Influence of vegetation clutter on the capacity of ground foraging bats to capture prey. *Journal of Applied Ecology* **47**, 850-858. doi.org/10.1111/j.1365-2664.2010.01820.x

Raison RJ, Woods PV, Khanna PK (1986) Decomposition and accumulation of litter after fire in sub-alpine eucalypt forests. *Australian Journal of Ecology* **11**, 9-19. doi.org/10.1111/j.1442-9993.1986.tb00913.x

Rayner L (2008) Variation in tree hollow availability in semi-arid woodlands of central western NSW. (Honours Thesis: Australian Catholic University)

Recher HF (1969) Bird species diversity and habitat diversity in Australia and North America. *The American Naturalist* **103**, 75-80

Recher HF, Holmes RT, Schulz M, Shields J, Kavanagh R (1985) Foraging patterns of breeding birds in eucalypt forest and woodland of southeastern Australia. *Australian Journal of Ecology* **10**, 399-419. doi.org/10.1111/j.1442-9993.1985.tb00902.x

Recher HF, Lunney D, Posamentier H (1975) A grand natural experiment – the Nadgee wildfire. *Australian Natural History* **18**, 150-63

Reddy S, Davalos LM (2003) Geographical sampling bias and its implications for conservation priorities in Africa. *Journal of Biogeography* **30**, 1719−1727. doi: 10.1046/j.1365-2699.2003.00946.x

Reeves J, Chen J, Wang XL, Lund R, Lu QQ (2007) A review and comparison of change point detection techniques for climate data. *Journal of Applied Meteorology and Climatology* **46**, 900−915. doi: 10.1175/JAM2493.1

Regos A, D’Amen M, Titeux N, Herrando S, Guisan A, Brotons L (2015) Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios. *Diversity and Distributions* **22**, 83-96. doi.org/10.1111/ddi.12375

Richards SA, Possingham HP, Tizard J (1999) Optimal fire management for maintaining community diversity. *Ecological Applications* **9**, 880-892. doi.org/10.1890/1051-0761(1999)009[0880:OFMFMC]2.0.CO;2

Richardson DM, van Wilgen BW, Lemaitre DC, Higgins KB, Forsyth GG (1994) A computer-based system for fire management in the mountains of the Cape Province, South Africa. *International Journal of Wildland Fire* **4**, 17-32. doi.org/10.1071/WF9940017

Ritter SM, Hoffman CM, Stewart JE, Zimmerman T (2018) The influence of prescribed crown fire on lodgepole pine dwarf mistletoe (*Arceuthobium americanum*) populations 33 years post-fire. *Forest Pathology* **48**, e12419. doi.org/10.1111/efp.12419

Roberts CP, Donovan VM, Nodskov SM, Keele EB, Allen CR, Wedin DA, Twidwell D (2020) Fire legacies, heterogeneity, and the importance of mixed-severity fire in ponderosa pine savannas. *Forest Ecology and Management* **459**, 117853. doi.org/10.1016/j.foreco.2019.117853

Robinson NM, Leonard SWJ, Ritchie EG, Bassett M, Chia EK, Buckingham S, Gibb H, Bennett AF, Clarke MF (2013) REVIEW: Refuges for fauna in fire-prone landscapes: their ecological function and importance. *Journal of Applied Ecology* **50**, 1321-1329. doi.org/10.1111/1365-2664.12153

Rochester CJ, Brehme CS, Clark DR, Stokes DC, Hathaway SA, Fisher RN (2010) Reptile and amphibian responses to large-scale wildfires in southern California. *Journal of Herpetology* **44**, 333-351. doi.org/10.1670/08-143.1

Rodrigo A, Sarda-Palomera F, Bosch J, Retana J (2008) Changes of dominant ground beetles in black pine forests with fire severity and successional age. *Ecoscience* **4**, 442-452. doi.org/10.2980/15-4-3117

Rollins MG, Morgan P, Swetnam T (2002) Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. *Landscape Ecology* **17**, 539-557. doi.org/10.1023/A:1021584519109

Romero-Calcaerrada R, Novillo CJ, Millington JDA, Gomex-Jiminez I (2008) GIS analysis of spatial patterns of human-caused wildfire ignition risk in the SW of Madrid (Central Spain). *Landscape Ecology* **23**, 341-354. doi.org/10.1007/s10980-008-9190-2

Romme WH, Whitby TG, Tinker DB, Turner MG (2016) Deterministic and stochastic processes lead the divergence in plant communities 25 years after the 1988 Yellowstone fires. *Ecological Monographs* **86**, 327-351. doi.org/10.1002/ecm.1220

Ross GJ (2015) Parametric and Nonparametric sequential change detection in R: The cpm Package. *Journal of Statistical Software* **66**, 1-20

Ross GJ, Tasoulis DK, Adams NM (2011) Nonparametric monitoring of data streams for changes in location and scale. *Technometrics* **53**, 379−389. doi.org/10.1198/TECH.2011.10069

Rotenberry JT (1985) The role of habitat in avian community composition: physiognomy or floristics? *Oecologia* **67**, 213-217

Rothermal RC (1972) A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115, USDA Forest Service, Intermountain Forest and Range Experiment Station (Ogden, UT)

Roy DP and Boschetti L (2009). Southern Africa validation of the MODIS, L3JRC and GlobCarbon burned-area products. *IEEE Transactions on Geoscience and Remote Sensing* **47**, 1032-1044. doi: 10.1109/TGRS.2008.2009000

Russell BG, Smith B, Augee ML (2003) Changes to a population of common ringtail possums (*Pseudocheirus peregrinus*) after bushfire. *Wildlife Research* **30**, 389-396. doi.org/10.1071/WR01047

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

Russell-Smith J, Yates CP, Whitehead PJ, Smith R, Craig R, Allan GE, Thackway R, Frakes I, Cridland S, Meyer MCP, Gill AM (2007) Bushfires 'down under': patterns and implications of contemporary Australian landscape burning. *International Journal of Wildland Fire* **16**, 361-377. doi.org/10.1071/WF07018

Sah JP, Ross MS, Snyder JR, Koptur S, Cooley HC (2006) Fuel loads, fire regimes, and post-fire fuel dynamics in Florida Keys pine forests. *International Journal of Wildland Fire* **15**, 463-478. doi.org/10.1071/WF05100

San-Miguel-Ayanz J, Schulte E, Schmuck G, Camia A, Strobl P, Libertà G, Giovando C, Boca R, Sedano F, Kempeneers P, McInerney D, Withmore C, Santos de Oliveira S, Rodrigues M, Durrant T, Corti P, Oehler F, Vilar L, Amatulli G (2012) Comprehensive monitoring of wildfires in Europe: the European Forest Fire Information System (EFFIS). In: *Approaches to Managing Disaster – Assessing*

Hazards, Emergencies and Disaster Impacts' (ed. J. Tiefenbacher), pp. 87–105 (InTech)

Saunders DA, Smith GT, Rowley I (1982) The availability and dimensions of tree hollows that provide nest sites for cockatoos (Psittaciformes) in Western Australia. *Australian Wildlife Research* **9**, 541-556. doi.org/10.1071/WR9820541

Sawyer R, Bradstock R, Bedward M, Morrison RJ (2018) Fire intensity drives post-fire temporal pattern of soil carbon accumulation in Australian fire-prone forests. *Science of the Total Environment* **610-611**, 1113-1124. doi.org/10.1016/j.scitotenv.2017.08.165

Saxon EC (1984) Anticipating the inevitable: a patch-burn strategy for fire management at Uluru (Ayers Rock-Mt Olga) National Park. (CSIRO Division of Wildlife and Rangelands Research: Melbourne)

Schimmel J, Granstrom A (1996) Fire severity and vegetation response the boreal Swedish forest. *Ecology* **77**, 1436-1450. doi.org/10.2307/2265541

Schoennagel T, Smithwick EAH, Turner MG (2008) Landscape heterogeneity following large fires: insights from Yellowstone National Park, USA. *International Journal of Wildland Fire* **17**, 742-753. doi.org/10.1071/WF07146

Schoennagel T, Veblen TT, Romme WH (2004) The interaction of fire, fuels and climate across Rocky Mountain forests. *BioScience* **54**, 661-676. doi.org/10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2

Shaw RE, James AI, Tuft K, Legge S, Cary GJ, Peakall R, Banks SC (2021) Unburnt habitat patches are critical for survival and in situ population recovery in a small mammal after fire. *Journal of Applied Ecology* **58**, 1325-1335. doi.org/10.1111/1365-2664.13846

Sheeren D, Mustiere S, Zucker JC (2009) A data-mining approach for assessing consistency between multiple representations in spatial databases. *International Journal of Geographical Information Science* **23**, 961−992. doi: 10.1080/13658810701791949

Shive KL, Sieg CH, Fule PZ (2013) Pre-wildfire management treatments interact with fire severity to have long lasting effects on post-wildfire vegetation response. *Forest Ecology and Management* **297**, 75-83. doi.org/10.1016/j.foreco.2013.02.021

Shlisky A, Alencar A, Manta M, Curran LM (2009) Overview: Global fire regime conditions, threats, and opportunities for fire management in the tropics. In: *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics* (ed. M.A. Cochrane), pp. 65-83 (Praxis Publishing, Chichester)

Short KC (2014) A spatial database of wildfire in the United States, 1992-2011. *Earth System Science Data* **6**, 1-27. doi:10.5194/ESSD-6-1-2014

Short KC (2015) Sources and implications of bias and uncertainty in a century of USA wildfire activity. *International Journal of Wildland Fire* **24**, 883−891. doi: 10.1071/WF14190

Shryock DF, Esque TC, Chen FC (2015) Topography and climate are more important drivers of long-term, post-fire vegetation assembly than time-since-fire in the Sonoran Desert, US. *Journal of Vegetation Science* **26**, 1134-1147. doi.org/10.1111/jvs.12324

Simard AJ (1991) Fire severity, changing scales, and how things hang together. *International Journal of Wildland Fire* **1**, 23-34. doi.org/10.1071/WF9910023

Simon MF, Pennington T (2012) Evidence for adaptation to fire regimes in the tropical savannas of the Brazilian Cerrado. *International Journal of Plant Sciences* **173**, 711-723. doi.org/10.1086/665973

Singh G, Kershaw AP, Clark R (1981) Quaternary vegetation and fire history in Australia. In: *Fire and the Australian Biota* (eds. A.M. Gill, R.H. Groves, and I.R. Noble), pp. 23-54 (Australian Academy of Science, Canberra)

Singh S, Smith AK, Blomberg SP (2002) Effect of a control burn on lizards and their structural environment in a eucalypt open-forest. *Wildlife Research* **29**, 447-454. doi.org/10.1071/WR01015

Sitters H, Christie F, Di Stefano J, Swan M, Collins P, York A (2014) Associations between occupancy and habitat structure can predict avian responses to disturbances: Implications for conservation management. *Forest ecology and Management* **331**, 227-236. doi.org/10.1016/j.foreco.2014.08.013

Sitters H, Di Stefano J, Christie FJ, Sunnucks P, York A (2015) Bird diversity increased after patchy prescribed fire: implications from a before-after control-impact study. *International Journal of Wildland Fire* **24**, 690-701. doi.org/10.1071/WF14123

Skinner CN (2003) A tree-ring based fire history of riparian reserves in the Klamath Mountains. In: *Californian riparian systems: processes and floodplain management, ecology and restoration* (ed. P.M. Faber), pp. 116-119. Riparian Habitat Joint Venture (Sacramento, CA)

Slatyer RO, Ferrar PJ (1977) Altitudinal variation in the photosynthetic characteristics of Snow Gum, *Eucalyptus pauciflora* Sieb. Ex Spreng. II. Effects of growth temperature under controlled conditions. *Australian Journal of Plant Physiology* **4**, 289-299. doi.org/10.1071/PP9770289

Smit IPJ, Smit CF, Govender N, van der Linde M, MacFadyen S (2013) Rainfall, geology and landscape position generate large-scale spatiotemporal fire pattern heterogeneity in an African savanna. *Ecography* **36**, 447-459. doi.org/10.1111/j.1600-0587.2012.07555.x

Smith AL, Bull CM, Driscoll DA (2013) Successional specialisation in a reptile community cautions against widespread planned burning and complete fire suppression. *Journal of Applied Ecology* **50**, 1178−1186. doi: 10.1111/1365-2664.12119

Smucker KM, Hutto RL, Steele BM (2005) Changes in bird abundance after wildfire: importance of fire severity and time since fire. *Ecological Applications* **15**, 1535-1549. doi.org/10.1890/04-1353

Soderquist TR, Mac Nally R (2000) The conservation value of mesic gullies in dry forest landscapes: mammal populations in the box-ironbark ecosystems of southern Australia. *Biological Conservation* **93**, 281-291. doi.org/10.1016/S0006-3207(99)00153-6

Sollmann R, White AM, Tarbill GL, Manley PN, Knapp EE (2016) Landscape heterogeneity compensates for fuel reduction treatment effects on Northern flying squirrel populations. *Forest Ecology and Management* **373**, 100-107. doi.org/10.1016/j.foreco.2016.04.041

Spies TA, Franklin JF, Thomas TB (1988) Coarse woody debris in Douglas-fir forests of western Oregon and Washington. *Ecology* **69**, 1689-1702. doi.org/10.2307/1941147

Spies TA, Hemstrom MA, Youngblood A, Hummel S (2004) Conserving old-growth forest diversity in disturbance-prone landscapes. *Conservation Biology* **20**, 351-362. doi.org/10.1111/j.1523-1739.2006.00389.x

Spies TA, Lindenmayer DB, Gill AM, Stephens SL, Agee JK (2012) Challenges and a checklist for biodiversity conservation in fire prone forests: perspectives from the Pacific Northwest of USA and Southeastern Australia. *Biological Conservation* **145**, 5-14. doi.org/10.1016/j.biocon.2011.09.008

SPSS: IBM Corp. (2017) IBM SPSS Statistics for Windows, version 25.0. (Armonk, NY: IBM Corp)

Srivastava SK, King L, Mitchell C, Weigand 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

Start AN (2015) The mistletoe flora of southern Western Australia, with a particular reference to hot relationships and fire. *Australian Journal of Botany* **63**, 636-646. doi.org/10.1071/BT15028

Stawski C, Kortner G, Nowack J, Geiser F (2015) The importance of mammalian torpor for survival in a post-fire landscape. *Biology Letters* **11**, 20150134. doi.org/10.1098/rsbl.2015.0134

Staver AC, Archibald S, Levin SA (2011) The global extent and determinants of savanna and forest as alternative biome states. *Science* **334**, 230-232. DOI: 10.1126/science.1210465

Staver AC, Bond WJ, Stock WD, Rensburg SJ, Waldram MS (2009) Browsing and fire interact to suppress tree density in an African savanna. *Ecological Applications* **19**, 1909-1919. doi.org/10.1890/08-1907.1

Steel ZL, Foster D, Coppoletta M, Lydersen JM, Stephens SL, Paudel A, Markwith SH, Merriam K, Collins BM (2021) Ecological resilience and vegetation transition in the face of two successive large wildfires. *Journal of Ecology* **109**, 3340-3355. doi.org/10.1111/1365-2745.13764

Steen DA, Osborne PA, Dovciak M, Patrick DA, Gibbs JP (2015) A preliminary investigation into the short-term effects of a prescribed fire on habitat quality for a snake assemblage. *Herpetological Conservation and Biology* **10**, 263-272

Stein A, Gerstner K, Kreft H (2014) Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales. *Ecology Letters* **17**, 866-880. doi.org/10.1111/ele.12277

Stephens SL, Ruth LW (2005) Federal forest-fire policy in the United States. *Ecological Applications* **15**, 532-542. doi.org/10.1890/04-0545

Sutherland EF, Dickman CR (1999) Mechanisms of recovery after fire by rodents in the Australian environment: a review. *Wildlife Research* **26**, 405-419. doi.org/10.1071/WR97045

Sutter RD, Wainscott SB, Boetsch JR, Palmer CJ, Rugg DJ (2015) Practical guidance for integrating data management into long-term ecological monitoring projects. *Wildlife Society Bulletin* **39**, 451−463. doi: 10.1002/wsb.548

Swan M, Di Stefano J, Greenfield A, Coulson G (2009) Fine-scale habitat selection by adult females swamp wallabies (*Wallabia bicolour*). *Australian Journal of Zoology* **56**, 309-309. doi.org/10.1071/ZO07051

Syphard AD, Franklin J, Keeley JE (2006) Simulating the effects of frequent fire on southern California coastal shrublands. *Ecological Applications* **16**, 1744-1756. doi.org/10.1890/1051-0761(2006)016[1744:STEOFF]2.0.CO;2

Syphard AD, Keeley JE (2016) Historical reconstructions of California wildfires by data source. *International Journal of Wildland Fire* **25**, 1221−1227. doi: 10.1071/WF16050

Syphard AD, Radeloff VC, Hawbaker TJ, Stewart SI (2009) Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems. *Conservation Biolog*y **23**, 758-769. doi.org/10.1111/j.1523-1739.2009.01223.x

Syphard AD, Radeloff VC, Keeley JE, Hawbaker TJ, Clayton MK, Stewart SE, Hammer RB (2007) Human influence on California fire regimes. *Ecological Applications* **17**, 1388-1402. doi.org/10.1890/06-1128.1

Tasker E, Dickman C (2004) Small mammal community composition in relation to cattle grazing ad associated burning in eucalypt forests of the Northern Tablelands of New South Wales. In: *Conservation of Australia's Forest Fauna*, *2nd edition*. (Ed. D. Lunney), pp. 721-740 (Royal Zoological Society of NSW, Sydney)

Tassicker AL, Kutt AS, Vanderduys E, Mangru S (2006) The effects of vegetation structure on the birds in a tropical savanna woodland in north-eastern Australia. *The Rangeland Journal* **28**, 139-152. doi.org/10.1071/RJ05029

Taylor JE, Fox BJ (2001*a*) Disturbance effects from fire and mining produce different lizard communities in eastern Australian forests. *Austral Ecology* **26**, 193-204. doi.org/10.1046/j.1442-9993.2001.01105.x

Taylor JE, Fox BJ (2001*b*) Assessing the disturbance impact on vegetation and lizard communities of fluoride pollution interacting with fire and mining in eastern Australia. *Austral Ecology* **26**, 321-337. doi.org/10.1046/j.1442-9993.2001.01117.x

Taylor JE, Monamy V, Fox BJ (1998) Flowering of *Xanthorrhoea fulva*: the effect of fire and clipping. *Australian Journal of Botany* **46**, 241-251. doi.org/10.1071/BT96100

Taylor RS, Watson SJ, Nimmo DG, Kelly LT, Bennett AF, Clarke MF (2012) Landscape-scale effects of fire on bird assemblages: does pyrodiversity beget biodiversity? *Diversity and Distributions* **18**, 519-529. doi.org/10.1111/j.1472-4642.2011.00842.x

Teague B, McLeod R, Pascoe S (2010) *2009 Victorian Bushfires Royal Commission. Final Report*. Victorian Government, Melbourne (www.royalcommission.vic.gov.au)

Teske C, Vanderhoof MK, Hawbaker TJ, Noble J, Hiers JK (2021) Using the Landsat burned area products to derive fire history relevant for fire management and conservation in the state of Florida, Southeastern USA. *Fire* **4**, 26. https://doi.org/10.3390/fire4020026

Tews J, Brose U, Grimm V, Tielborger K, Wichmann MC, Schwager M, Jeltsch F (2004) Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. *Journal of Biogeography* **31**, 79-92. doi.org/10.1046/j.0305-0270.2003.00994.x

Thackway R, Cresswell ID (Eds) (1995). An Interim Biogeographic Regionalisation for Australia: a framework for establishing the national system of reserves. Version 4.0. Australian Nature Conservation Agency (Canberra: Australia)

Theobold DM, Romme WH (2007) Expansion of the US wildland-urban interface. *Landscape and Urban Planning* **83**, 340-354. doi.org/10.1016/j.landurbplan.2007.06.002

Tidemann CR, Flavel SC (1987) Factors affecting choice of diurnal roost site by tree-hole bats (*Microchiroptera*) in southeastern Australia. *Australian Wildlife Research* **14**, 459-473. doi.org/10.1071/WR9870459

Tingley MW, Beissinger SR (2009) Detecting range shifts from historical species occurrences: new perspectives on old data. *Trends in Ecology and Evolution* **24**, 625−633. doi.org/10.1016/j.tree.2009.05.009

Todd SK and Jewkes HA (2006) Wildland fire in Alaska: a history of organised fire suppression and management in the last frontier. Agricultural and Forestry Experiment Station Bulletin No. 114, (University of Alaska: Fairbanks, AK)

Tolhurst KG, Flinn DW, Lyon RH, Wilson AAG, Foletta I (1992) Ecological effects of fuel reduction burning in a dry sclerophyll forest. A summary of principal research findings and their management implications. Department of Conservation and Environment (Melbourne, Australia)

Trainor CR, Woinarski JCZ (1994) Responses of lizards to three experimental fires in the savanna forests of Kakadu National Park. *Wildlife Research* **21**, 131-148. doi.org/10.1071/WR9940131

Tran C, Wild C (2000) A review of current knowledge and literature to assist in determining ecologically sustainable fire regimes for southeast Queensland region. (Griffith University & SEQ Fire and Biodiversity Consortium, Gold Coast, QLD)

Tsafrir A, Osem Y, Shemesh H, Carmel Y, Soref C, Ovadia O (2019) Fire season modifies the perennial plant community composition through a differential effect on obligate seeders in eastern Mediterranean woodlands. *Applied Vegetation Science* **22**, 115-126. doi.org/10.1111/avsc.12408

Turner MG, Baker WL, Peterson CJ, Peet RK (1998) Factors influencing succession: lessons from large, infrequent natural disturbances. *Ecosystems* **1**, 511-523. doi.org/10.1007/s100219900047

Underwood EC, Viers JH, Klausmeyer KR, Cox RL, Shaw MR (2009) Threats and biodiversity in the Mediterranean biome. *Diversity and Distributions* **15**, 188-197. doi.org/10.1111/j.1472-4642.2008.00518.x

van Wagtendonk JW, van Wagtendonk KA, Thode AE (2012) Factors associated with the severity of intersecting fires in Yosemite National Park, California, USA. *Fire Ecology* **8**, 11-31. doi.org/10.4996/fireecology.0801011

Vazquez A, Moreno JM (2001) Spatial distribution of forest fires in Sierra de Gredos (Central Spain). *Forest Ecology and Management* **147**, 55-65. doi.org/10.1016/S0378-1127(00)00436-9

Vasconcelos HL, Pacheco R, Silva RC, Vasconcelos PB, Lopes CT, Costa AN, Bruna EM (2009) Dynamics of the leaf-litter arthropod fauna following fire in a neotropical woodland savanna. *PlosOne* **4**: e7762. doi.org/10.1371/journal.pone.0007762 van de Water K, North M (2010). Fire history of coniferous riparian forests in the Sierra Nevada. *Forest Ecology and Management* **260**, 384-395. doi.org/10.1016/j.foreco.2010.04.032

Van Dyke F, Van Kley SE, Page CE, Van Beek JG (2004) Restoration efforts for plant and bird communities in tallgrass prairies using prescribed burning and mowing. *Restoration Ecology* **12**, 575-585. doi.org/10.1111/j.1061-2971.2004.00352.x

Van Etten EJB, Burrows ND (2018) Fire regimes and ecology of arid Australia. In: *On the Ecology of Australia's Arid Zone* (ed. H. Lambers), pp. 243-282 (Springer Nature Publishing: Cham, Switzerland)

van Wilgen BW, Forsyth GG, De Klerk H, Das S, Khuluse S, Schmitz P (2010). Fire management in Mediterranean-climate shrublands: a case study from the Cape fynbos, South Africa. *Journal of Applied Ecology* **47**, 631-638. doi.org/10.1111/j.1365-2664.2010.01800.x

van Wilgen BW, Govender N, Forsyth GG, Kraaij T (2011) Towards adaptive fire management for biodiversity conservation: Experience in South African National Parks. *Koedoe* **53**, 96-104

van Wilgen BW, Govender N, MacFayden S (2008). An assessment of the implementation and outcomes of recent changes to fire management in the Kruger National Park. *Koedoe* **50**, 22-31

Veblen TT, Kitzberger T, Donnegan J (2000) Climatic and human influences on fire regimes in Ponderosa pine forests in the Colorado front range. *Ecological Applications* **10**, 1178-1195. doi.org/10.1890/1051-0761(2000)010[1178:CAHIOF]2.0.CO;2

Vernes K, Dunn L (2009) Mammal mycophagy and fungal spore dispersal across a steep environmental gradient in eastern Australia. *Austral Ecology* **34**, 69-76. doi.org/10.1111/j.1442-9993.2008.01883.x

Walker J (1981) Fuel dynamics in Australian Vegetation. In: *Fire and the Australian Biota* (eds. A.M. Gill, R.H. Groves, and I.R. Noble), pp. 101-127 (Australian Academy of Science: Canberra)

Wan HY, Cushman SA, Ganey JL (2020) The effects of scale in quantifying fire impacts on species habitats. *Fire Ecology* **16**, 9. doi.org/10.1186/s42408-020-0068-2

Ward M, Tulloch AIT, Radford JQ, Williams BA, Reside AE, MacDonald SL, Mayfield HJ, Maron M, Possingham HP, Vine SJ, O'Connor JL, Massingham EJ, Greenville AC, Woinarski JCZ, Garnett ST, Lintermans M, Scheele BC, Carwardine J, Nimmo DG, Lindenmayer DB, Kooyman RM, Simmons JS, Sonter LJ, Watson JEM (2020) Impact of the 2019-2020 mega-fires on Australian fauna habitat. *Nature Ecology and Evolution* **4**, 1321-1326. doi.org/10.1038/s41559-020-1251-1

Watson DM (2001*b*) Mistletoe – a keystone resource in forests and woodlands worldwide. *Annual Review of Ecology and Systematics* **32**, 219-249

Watson P (2001*a*). The role and use of fire for biodiversity conservation in Southeast Quuensland: fire management guidelines derived from ecological research. (SEQ Fire and Biodiversity Consortium: Brisbane, QLD)

Watson PJ, Bradstock R, Morris EC (2009) Fire frequency influences composition and structure of the shrub layer in an Australian subcoastal temperate grassy woodland. *Austral Ecology* **34**, 218-232. doi.org/10.1111/j.1442-9993.2008.01924.x

Watson DM, McGregor HW, Spooner PG (2011) Hemiparasitic shrubs increase resource availability and multi-trophic diversity of eucalypt forest birds. *Functional Ecology* **150**, 889-899. doi: 10.1111/j.1365-2435.2011.01839.x

Watson SJ, Taylor RS, Nimmo DG, Kelly LT, Haslem A, Clarke MF, Bennett AF (2012) Effects of time since fire on birds: How informative are generalized fire response curves for conservation management? *Ecological Applications* **22**, 685-696. doi.org/10.1890/11-0850.1

Watson J, Watson A, Paull D, Freundenberger D (2002) Woodland fragmentation is causing the decline of species and functional groups of birds in southeastern Australia. *Pacific Conservation Biology* **8**, 261-270. doi.org/10.1071/PC030261

Webb JK, Shine R, Pringle RM, Lannoo MJ (2005) Canopy removal restores habitat quality for an endangered snake in a fire suppressed landscape. *Copeia* **4**, 894-900. doi.org/10.1643/0045-8511(2005)005[0894:CRRHQF]2.0.CO;2

Weber MG, Flannigan MD (1997) Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. *Environmental Reviews* **5**, 145−166. doi: 10.1139/a97-008

Webster CR, Jenkins MA (2005) Coarse woody debris dynamics in the southern Appalachians as affected by topographic position and anthropogenic disturbance history. *Forest Ecology and Management* **217**, 319-330. doi.org/10.1016/j.foreco.2005.06.011

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* **313**, 940-943. doi: 10.1126/science.1128834

Westerling AL, Turner MG, Smithwick EAH, Romme WH, Ryan MG (2011) Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *PNAS* **108**, 13165-13170. doi.org/10.1073/pnas.1110199108

Whelan RJ (1995) *The Ecology of Fire*. Cambridge University Press (England)

Whelan RJ (2002) Managing fire regimes for conservation and property protection. *Conservation Biology* **16**, 1659-1661. doi.org/10.1046/j.1523-1739.2002.02091.x

Whelan RJ (2009) The ecology of fire: developments since 1995 and outstanding questions. *Proceedings of the Royal Society of Queensland* **115**, 59-68

Whelan RJ, Ward S, Hogbin P, Wasley J (1996) Responses of heathland *Antechinus stuartii* to the Royal National Park wildfire in 1994. *Proceedings of the Linnean Society of New South Wales* **116**, 97-108

Whitlock C, Higuera PE, McWethy DB, Briles CE (2013) Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. *The Open Ecology Journal* **6**, 6-23. DOI: 10.2174/1874213001003020006

Wittkuhn RS, Hamilton T (2010) Using fire history data to map temporal sequences of fire return intervals and seasons. *Fire Ecology* **6**, 97−114. doi: 10.4996/fireecology.0602097

Williams RJ, Cook GD, Gill AM, Moore PHR (1999) Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Austral Ecology* **24**, 50-59. doi.org/10.1046/j.1442-9993.1999.00946.x

Williams SE, Marsh H, Winter J (2002) Spatial scale, species diversity and habitat structure: small mammals in Australian tropical rain forest. *Ecology* **83**, 1317-1329. doi.org/10.1890/0012-9658(2002)083[1317:SSSDAH]2.0.CO;2

Wilson BA (1996) Fire effects on vertebrate fauna and implications for fire management and conservation. In: *Fire and Biodiversity: The Effects and Effectiveness of Fire Management.* Biodiversity Series Paper no. 8. (ed. J.R. Merrick), Proceedings of the Conference 8-9th October 1994, Footscray, Melbourne. (Biodiversity Unit, Department of Environment, Sport and Territories, Canberra, Australia)

Wilson MF (1974) Avian community organisation and habitat structure. *Ecology* **55**, 1017-1029. doi.org/10.2307/1940352

Wilson BA, Kuehs J, Valentine LE, Sonneman T, Wolfe KM (2014) Guidelines for ecological burning regimes in Mediterranean ecosystems: a case study in *Banksia* woodlands in Western Australia. *Pacific Conservation Biology* **20**, 57-74. doi.org/10.1071/PC140057

Wilson S, Swan G (2003) *A complete guide to reptiles of Australia*. (New Holland, Sydney)

Woinarski JCZ (1999) Fire and Australian birds: a review in Australia's Biodiversity. In: *Responses to Fire: Plants, Birds and Invertebrates. Biodiversity Technical Paper No. 1*. (eds. J.C.Z Woinarski, A.M. Gill, and A. York) (Department of the Environment and Heritage, Commonwealth of Australia)

Woinarski JCZ, Armstrong M, Brennan K, Fisher A, Griffiths AD, Hill B, Milne DJ, Palmer C, Ward S, Watson M, Winderlich S, Young S (2010) Monitoring indicates rapid and severe decline of native small mammals in Kakadu National Park, northern Australia. *Wildlife Research* **37**, 116-126. doi.org/10.1071/WR09125

Woinarski JCZ, Brock C, Fisher A, Milne D, Oliver B (1999) Response of birds and reptiles to fire regimes on pastoral land in the Victoria River District, Northern Territory. *The Rangeland Journal* **21**, 24-38. doi.org/10.1071/RJ9990024

Woinarski JCZ, Burbudge AA, Harrison PL (2015) Ongoing unraveling of a continental fauna: Decline and extinction of Australian mammals since European settlement. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 4531-4540. doi.org/10.1073/pnas.1417301112

Woinarski JC, Recher HF (1997) Impact and response: a review of the effects of fire on the Australian avifauna. *Pacific Conservation Biology* **3**, 183-205. doi.org/10.1071/PC970183

Woinarski JCZ, Winderlich S (2014). A strategy for the conservation of threatened species and threatened ecological communities in Kakadu National Park 2014 – 2024. Northern Australia Hub, National Environmental Research Program (Charles Darwin University, Darwin)

Wood SW, Murphy BP, Bowman DMJS (2011). Firescape ecology: how topography determines the contrasting distribution of fire and rainforest in the south-west of the Tasmanian Wilderness World Heritage Area. *Journal of Biogeography* **38**, 1807-1820. https://doi.org/10.1111/j.1365-2699.2011.02524.x

Woodall CW, Liknes GC (2008) Relationship between forest fine and coarse woody debris carbon stocks across latitudinal gradients in the United States as an indicator of climate change effects. *Ecological Indicators* **8**, 686-690. doi.org/10.1016/j.ecolind.2007.11.002

Wormington KR, Lamb D, McCallum HI, Moloney DJ (2003) The characteristics of six species of living hollow-bearing trees and their importance for arboreal mammals in the dry sclerophyll forests of southeast Queensland, Australia. *Forest Ecology and Management* **182**, 75-92. doi.org/10.1016/S0378-1127(03)00010-0

Valentine LE, Reaveley A, Johnson B, Fisher R, Wilson BA (2012) Burning in Banksia woodlands: How does the fire-free period influence reptile communities? *Plos One* **7**: e344448. doi.org/10.1371/journal.pone.0034448

Yang J, He HS, Shifley SR (2008) Spatial controls of occurrence and spread of wildfires in the Missouri Ozark highlands. *Ecological Applications* **18**, 1212-1225. doi.org/10.1890/07-0825.1

Yang J, He HS, Shifley SR, Gustafson EJ (2007) Spatial patterns of modern period human-caused fire occurrence in the Missouri Ozark highlands. *Forest Science* **53**, 1-15. doi.org/10.1093/forestscience/53.1.1

Yang W, Ma K, Kreft H (2013) Geographical sampling bias in a large distributional database and its effects on species richness-environmental models. *Journal of Biogeography* **40**, 1415−1426. doi: 10.1111/jbi.12108

York A (1999) Long-term effects of frequent low-intensity burning on the abundance of litter-dwelling invertebrates in coastal blackbutt forests of southeastern Australia. *Journal of Insect Conservation* **3**, 191-199. doi.org/10.1023/A:1009643627781

York A (2000) Long-term effects of frequent low-intensity burning on ant communities in coastal blackbutt forests of southeastern Australia. *Austral Ecology* **25**, 83-98. doi.org/10.1046/j.1442-9993.2000.01014.x

Zeileis A, Kleiber C, Kraemer W, Hornik K (2003) Testing and dating of structural changes in practice. *Computational Statistics and Data Analysis* **50**, 2987-3008. doi.org/10.1016/S0167-9473(03)00030-6

Appendix 1: Supplementary materials for Chapter Two

For each attribute sampled in the pilot study, graphs of the mean, standard deviation and 95% confidence intervals per sample unit used to compare the ten alternative protocols to the raw data (see Chapter 2.2.4).

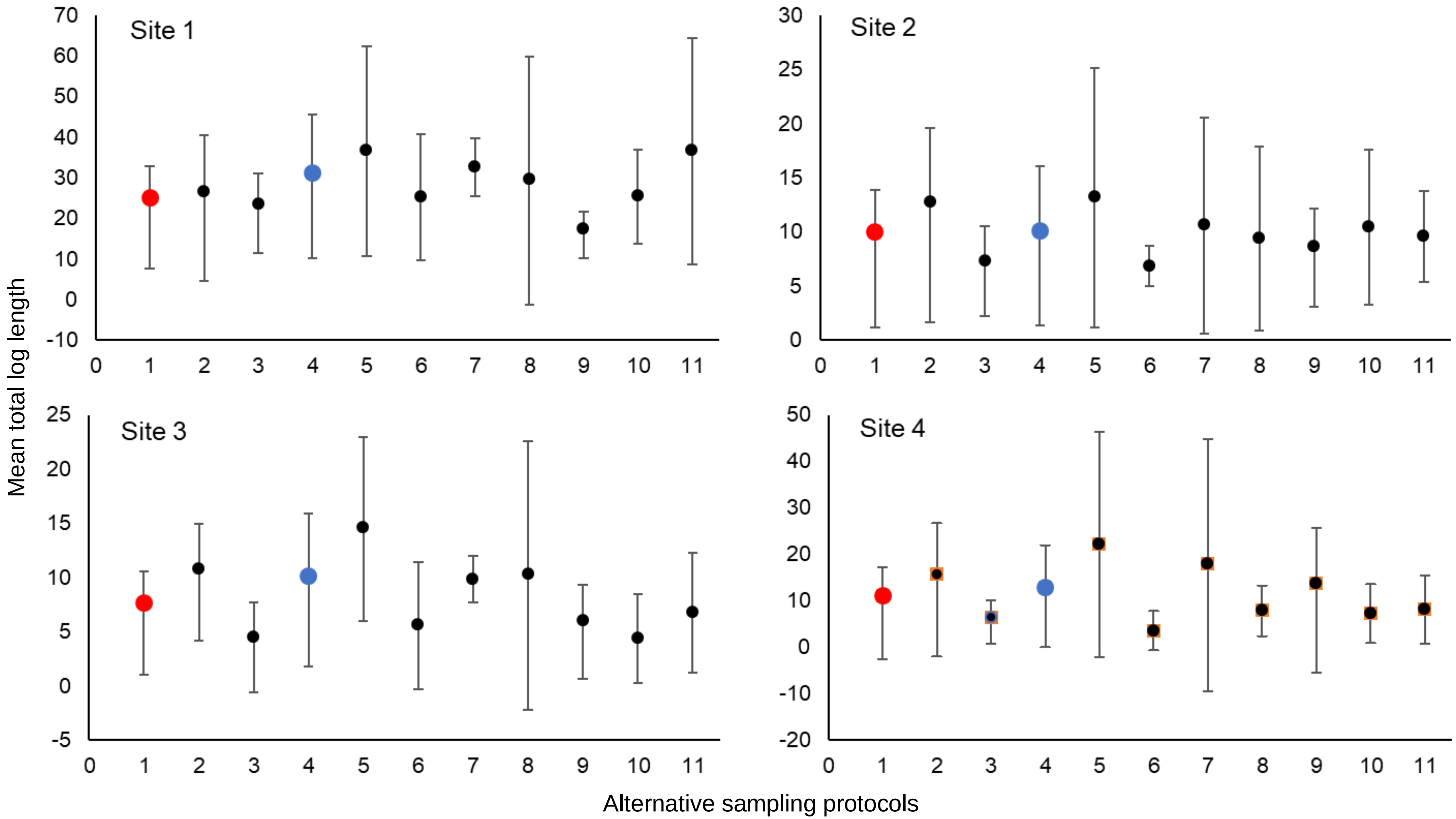


Figure A1.1 Mean total log length (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

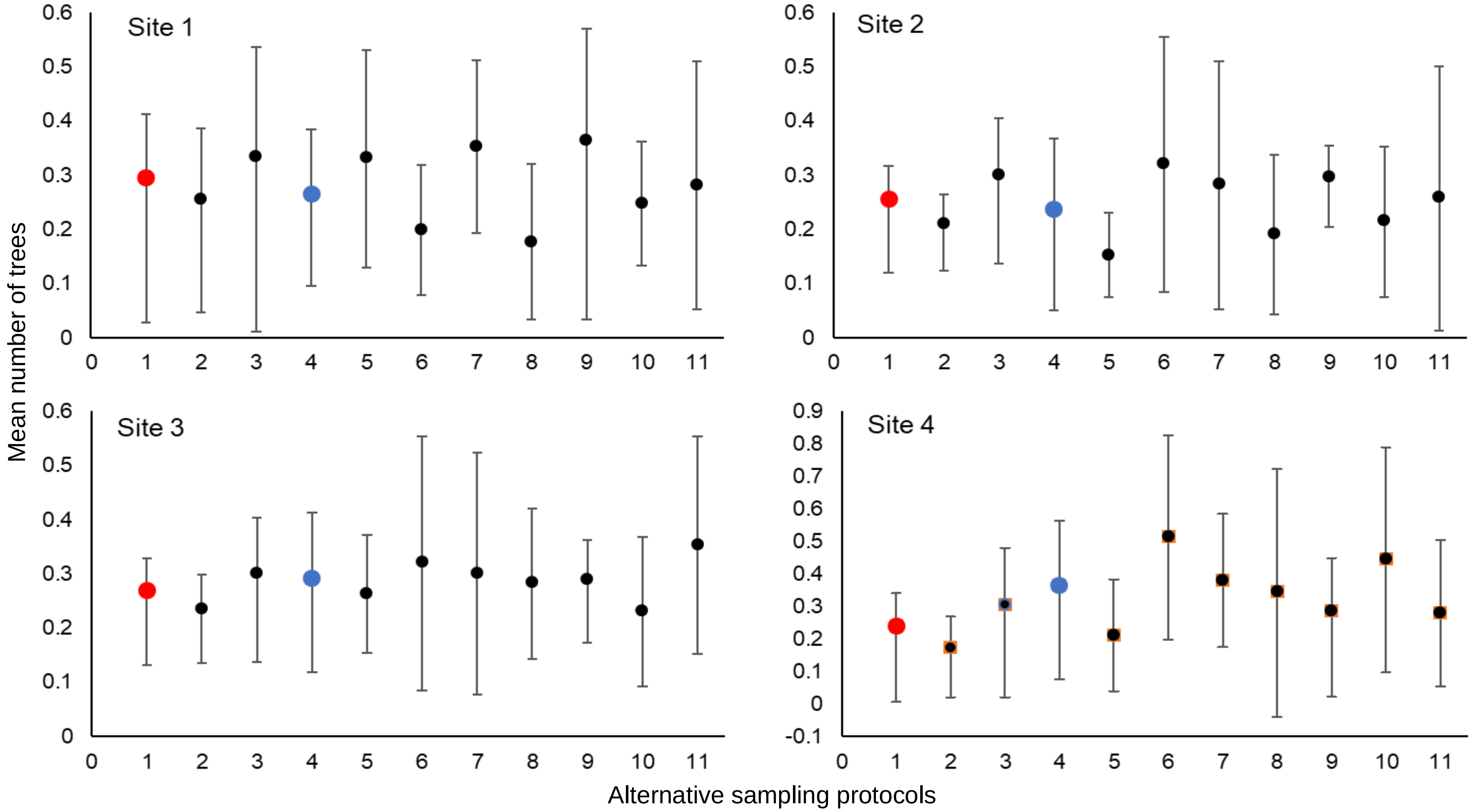


Figure A1.2 Mean number of trees (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

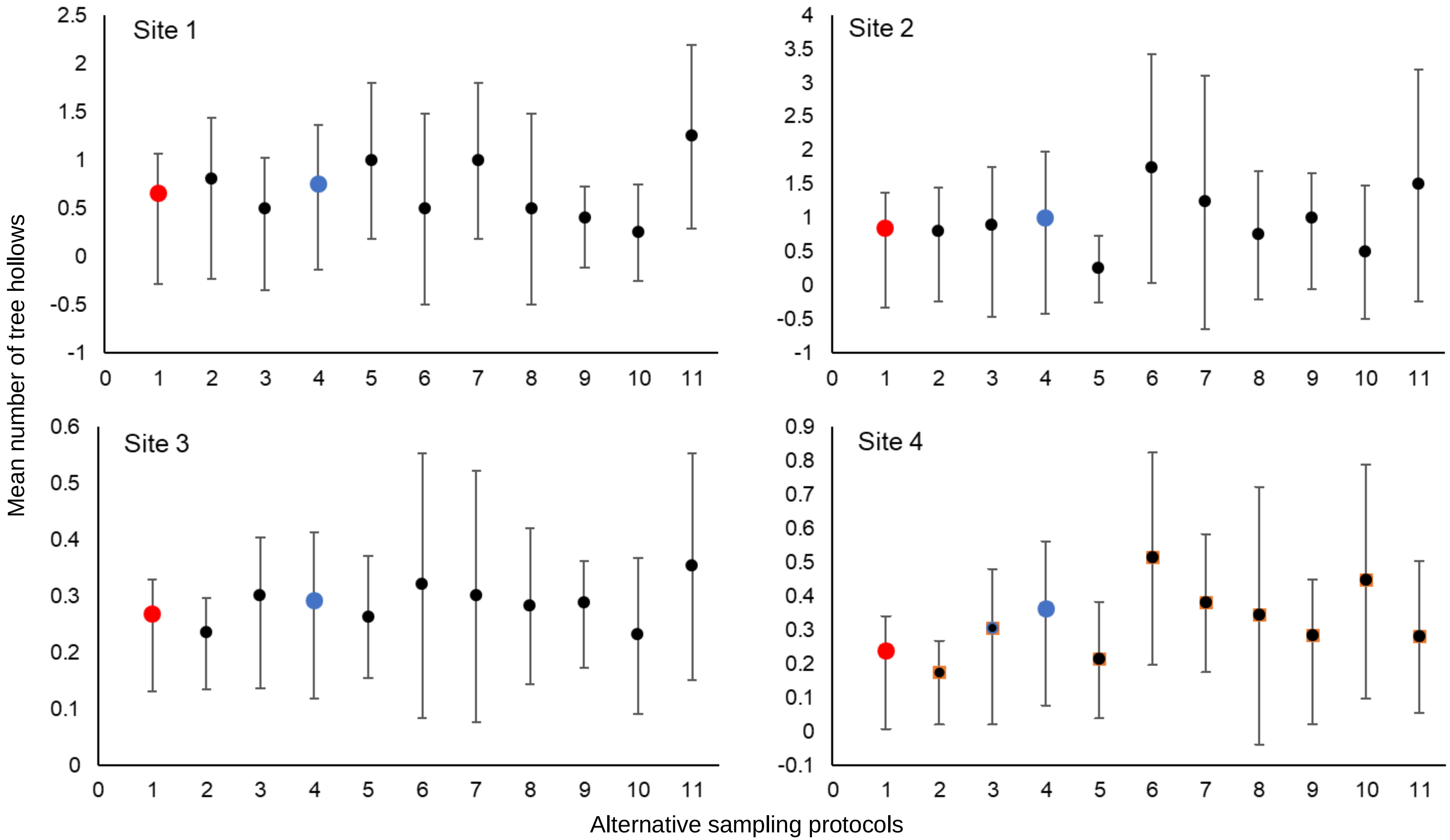


Figure A1.3 Mean number of tree hollows (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

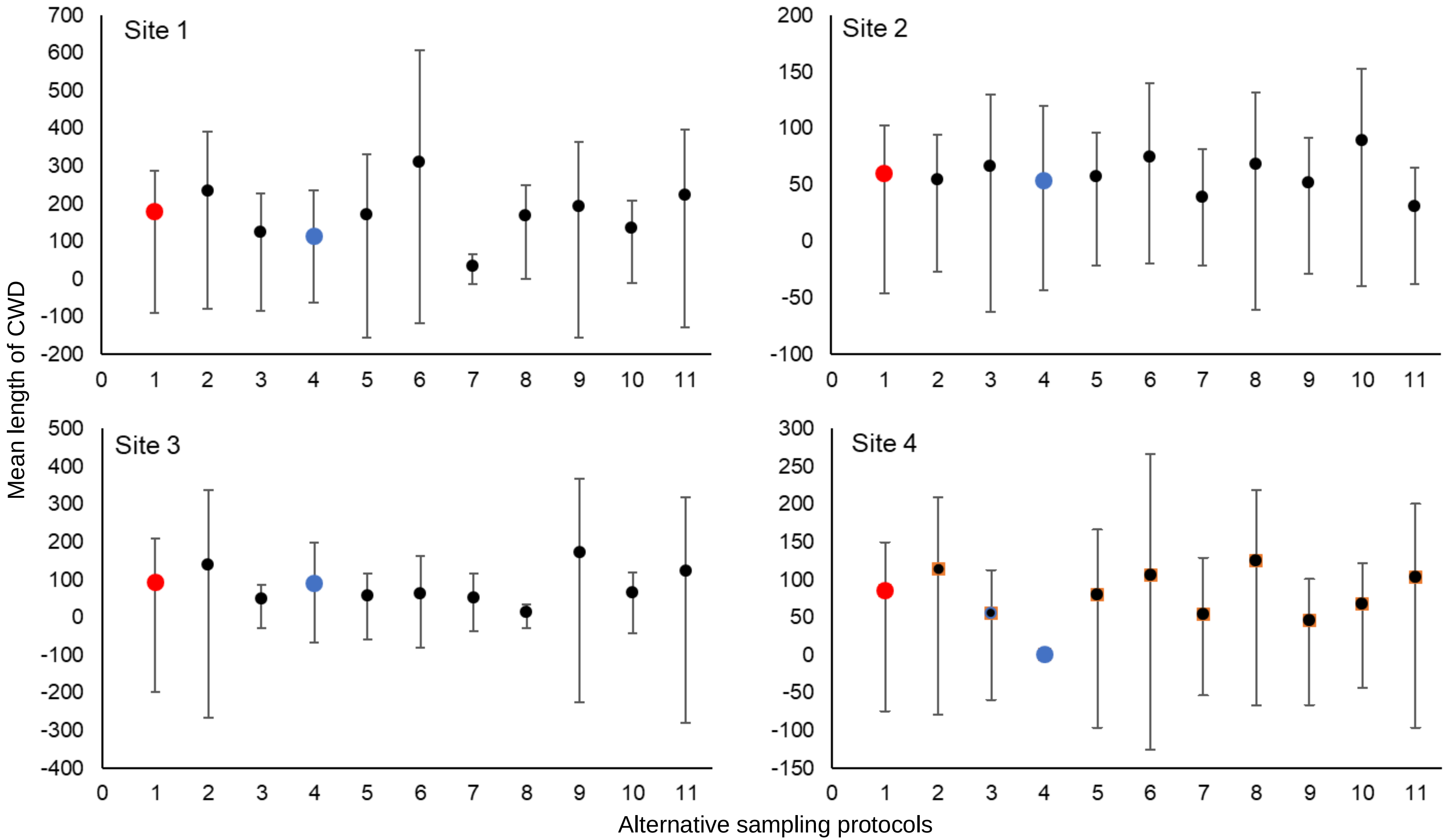


Figure A1.4 Mean length of CWD (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

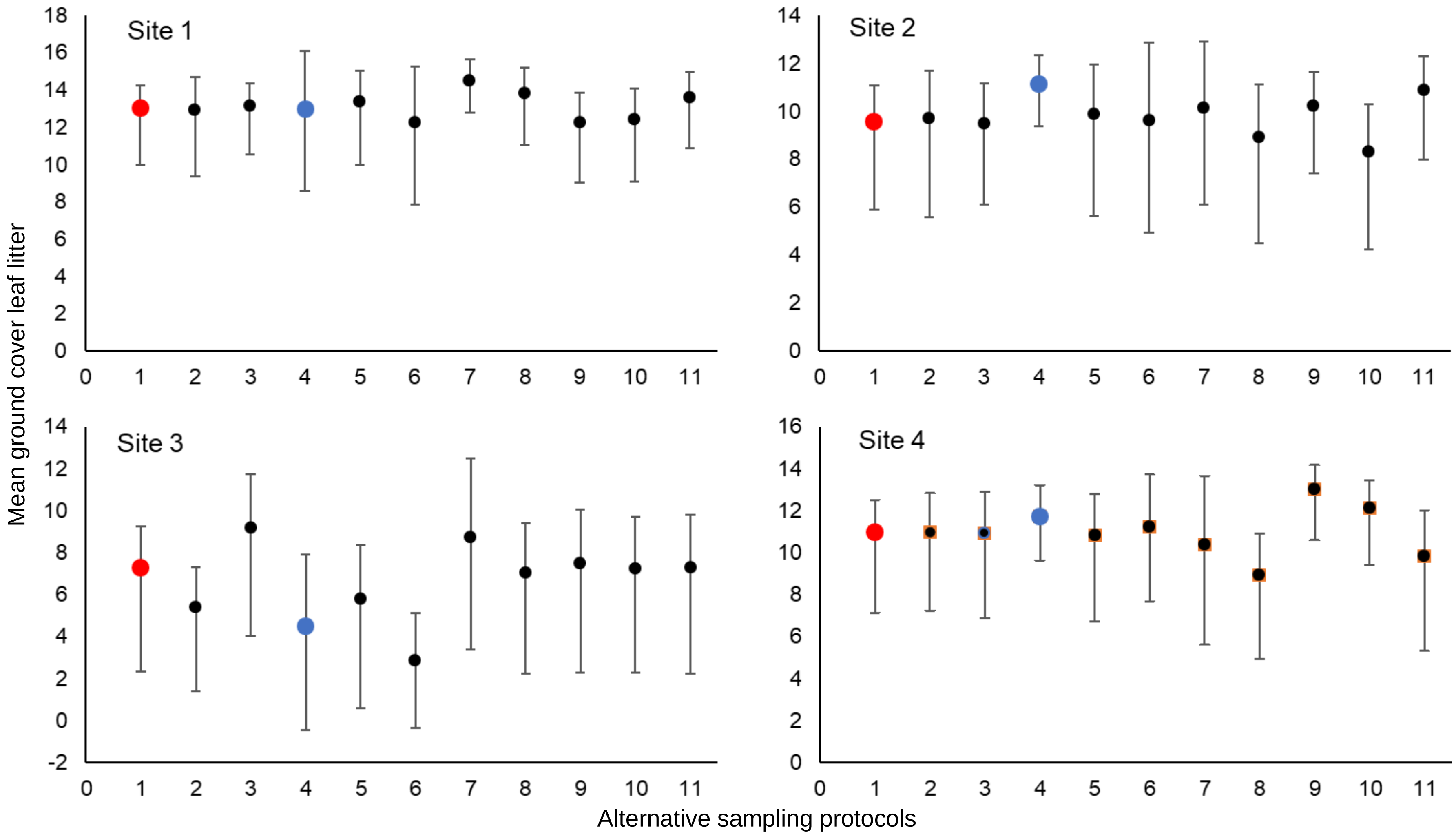


Figure A1.5 Mean ground cover leaf litter (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

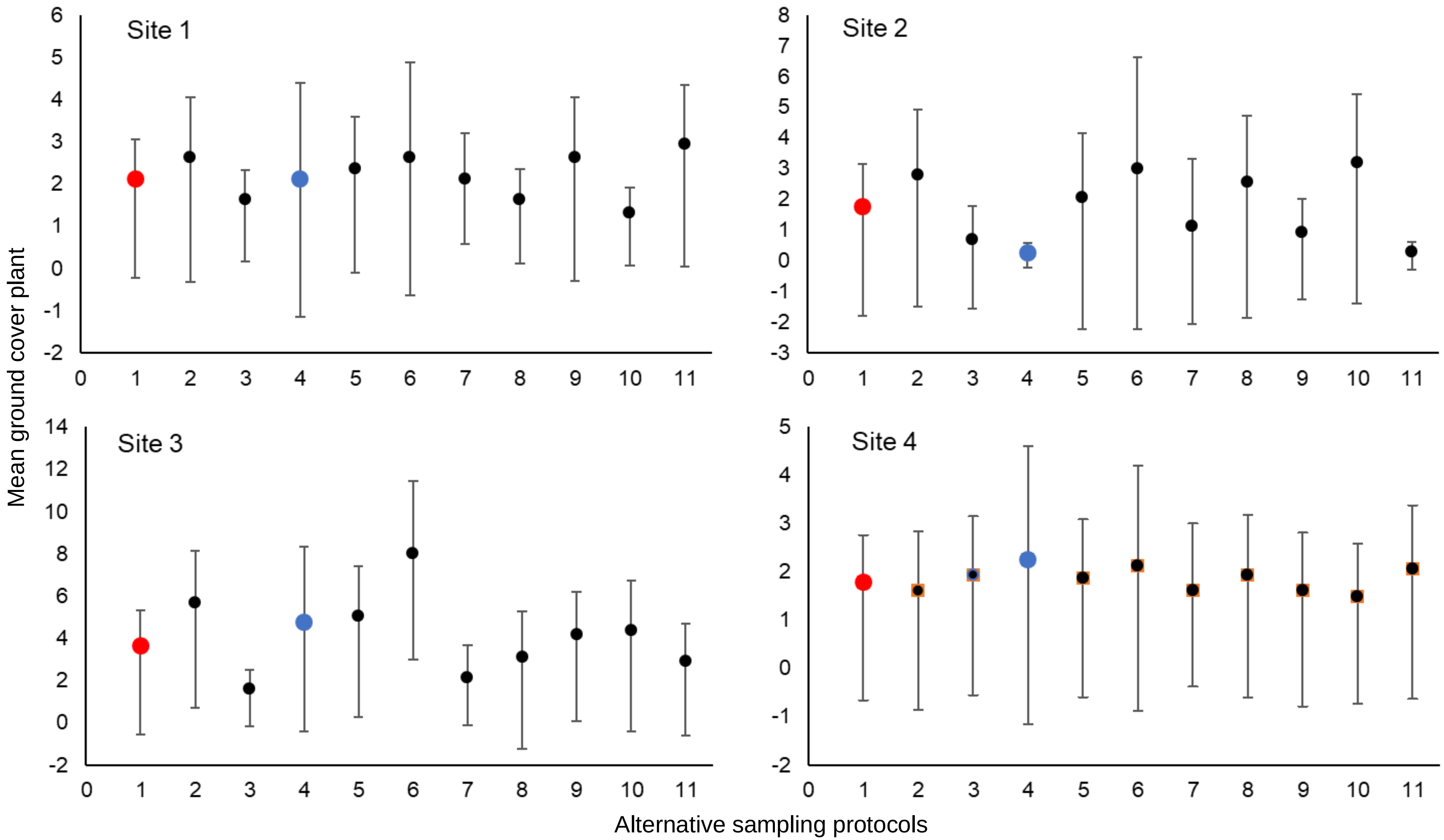


Figure A1.6 Mean ground cover plant (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

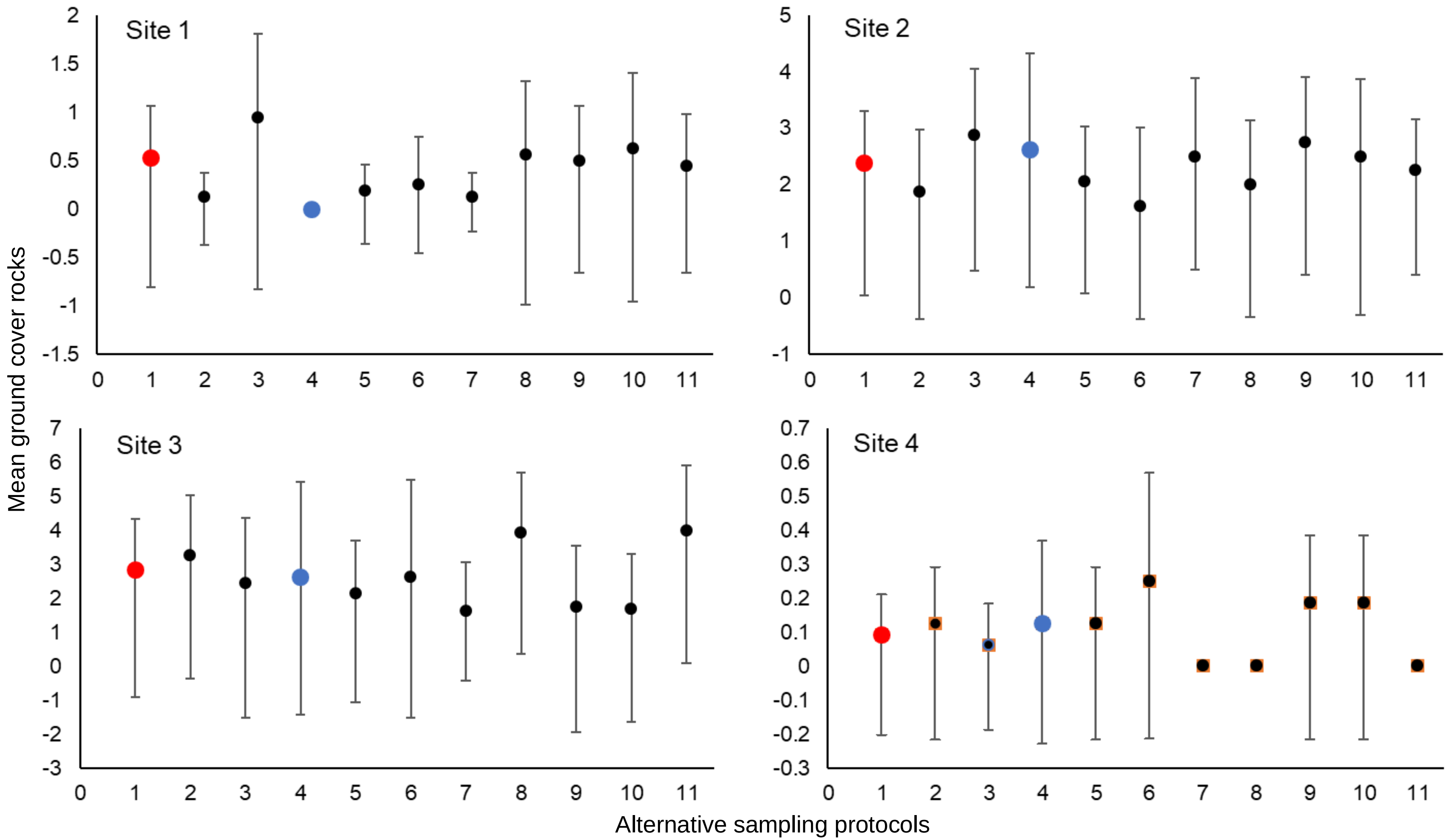


Figure A1.7 Mean ground cover rocks (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

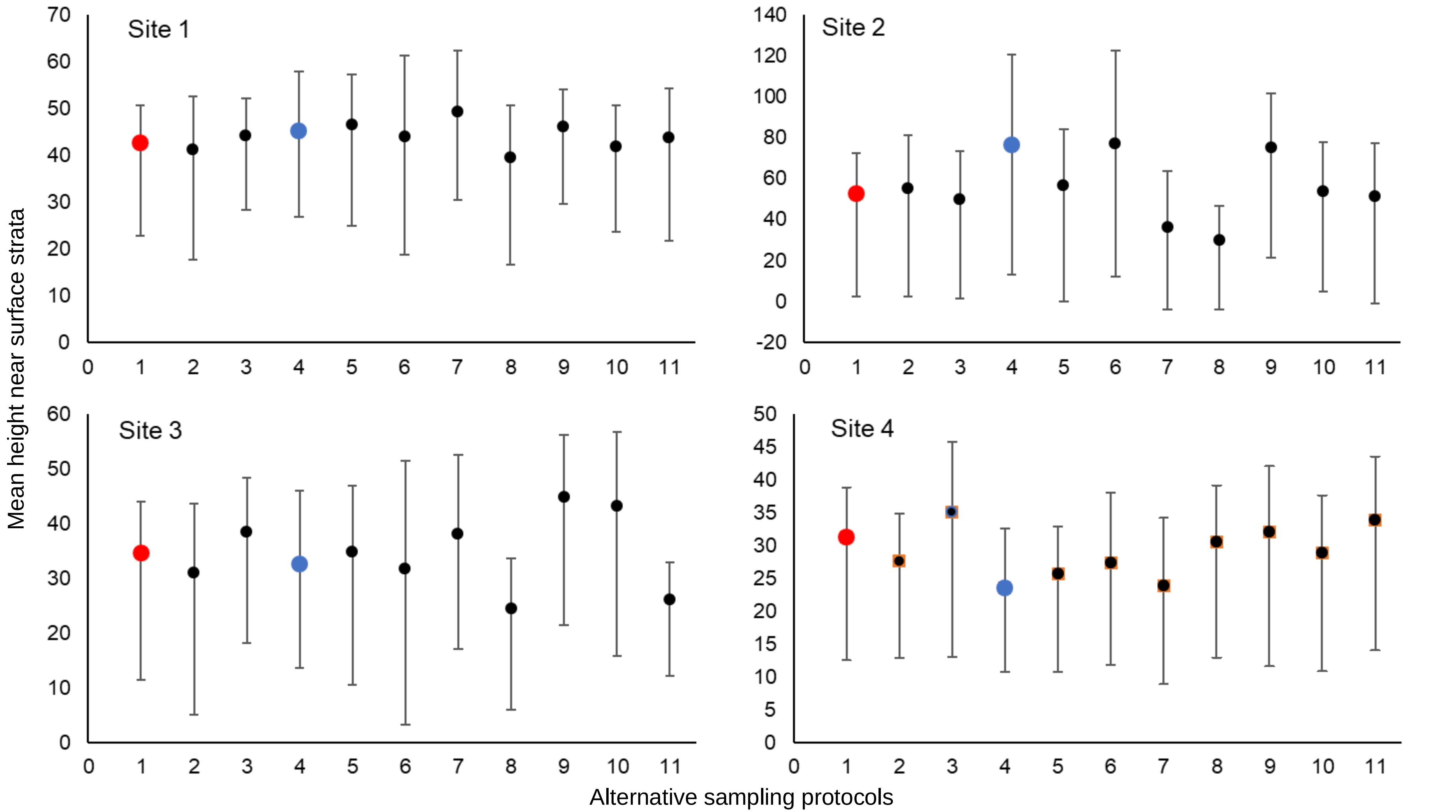


Figure A1.8 Mean height near surface strata (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

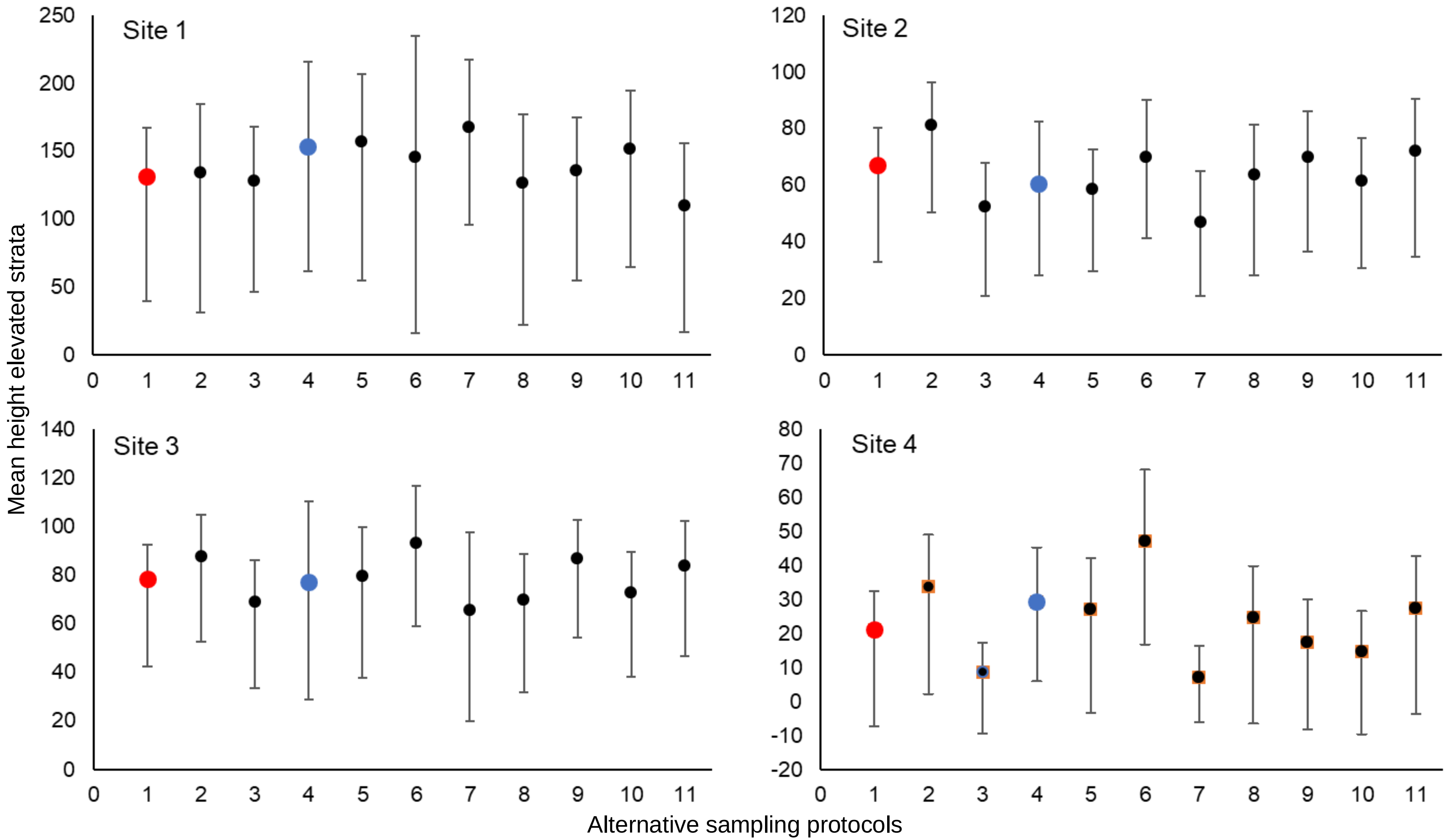


Figure A1.9 Mean height elevated strata (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

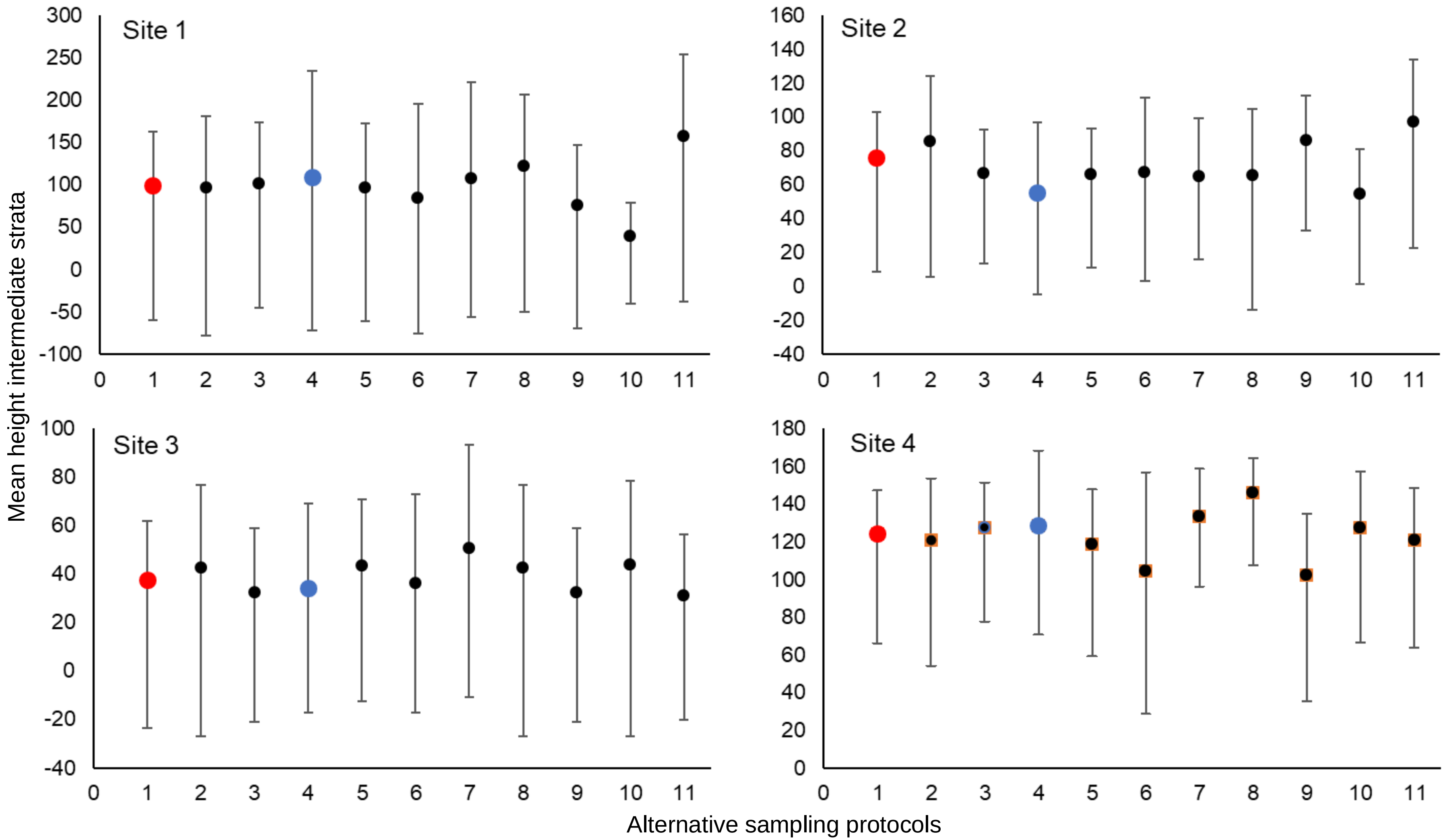


Figure A1.10 Mean height intermediate strata (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

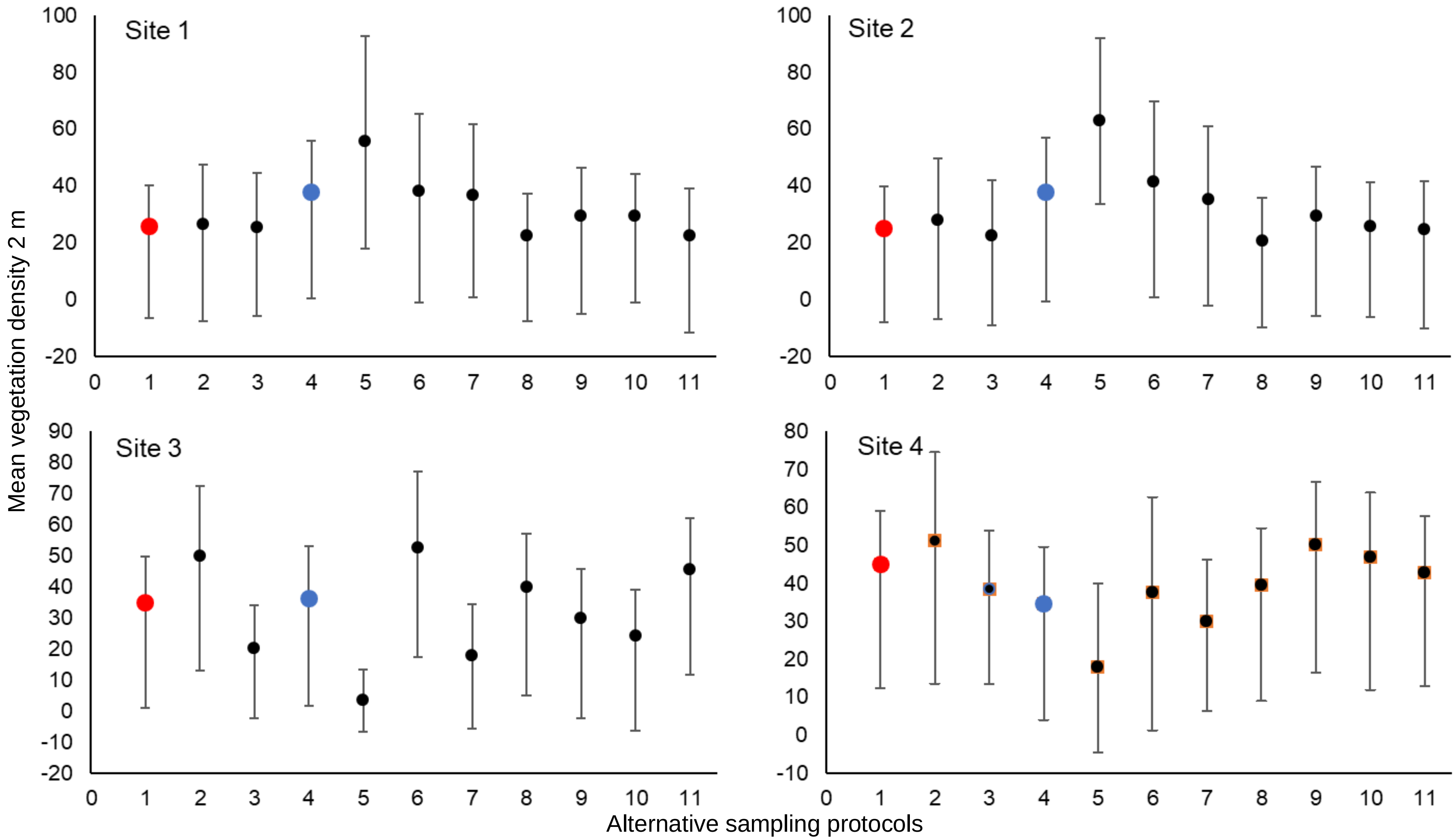


Figure A1.11 Mean vegetation density 2 m (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

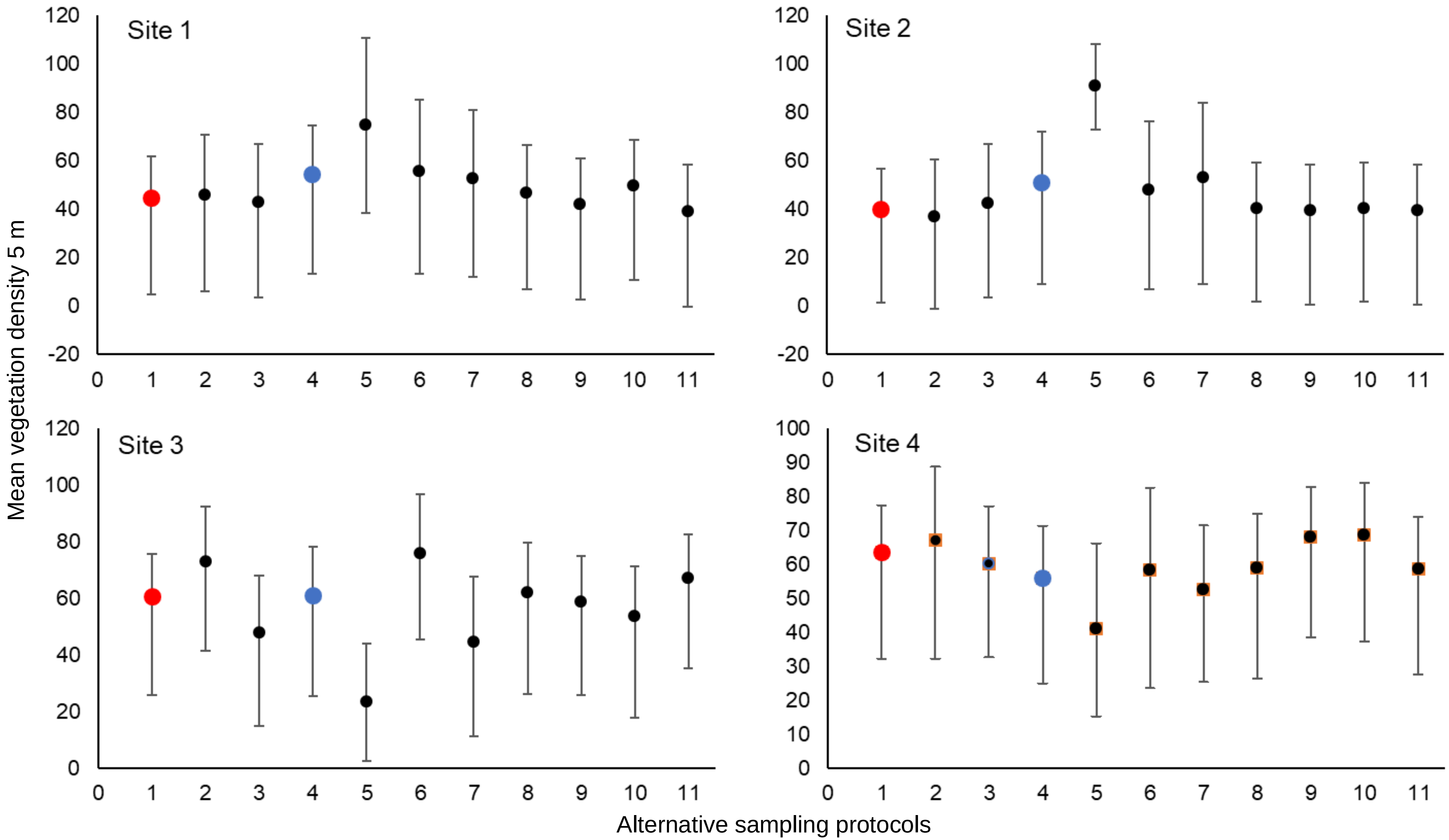
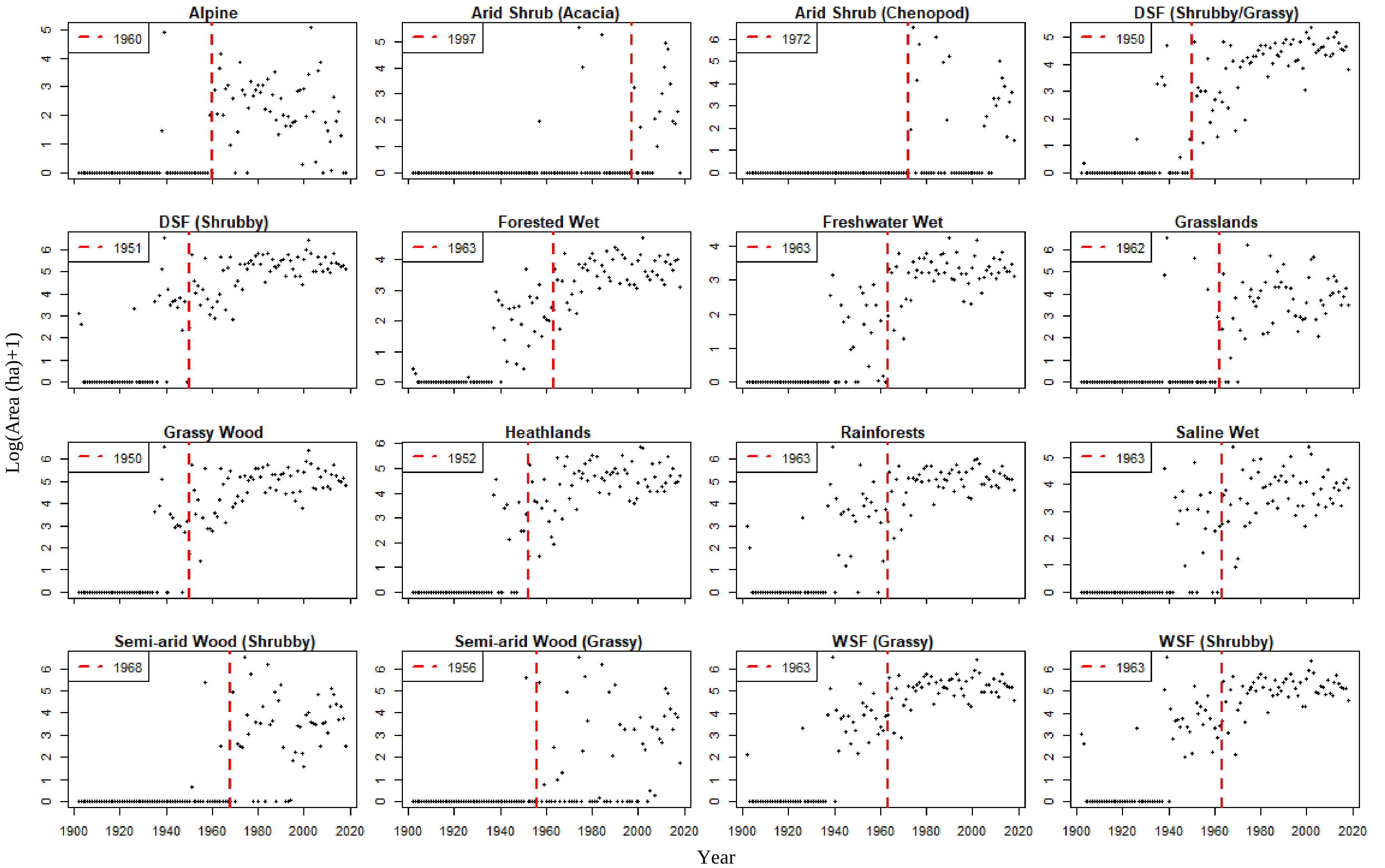


Figure A1.12 Mean vegetation density 5 m (std dev. and 95% confidence intervals) at Sites 1 – 4, actual site data in red, option taken in blue, alternatives in black (axis on different scales)

Appendix 2: Supplementary materials for Chapter Three

Graphs of change points identified by each of the each of the seven change point methods used (see Chapter 3.2.6) to test area burnt recorded in the database between 1902 and 2018 for each vegetation formation, the whole of NSW, and areas within NPWS Estate. Additionally, a list of records of fires found in Trove newspaper archives not found in the NSW fire database (see Chapter 3.3.2).

(*a*)


Alpine
1960
Arid Shrub (Acacia)
1997
Arid Shrub (Chenopod)
1972
DSF (Shrubby/Grassy)
1950
DSF (Shrubby)
1951
Forested Wet
1963
Freshwater Wet
1963
Grasslands
1962
Grassy Wood
1950
Heathlands
1952
Rainforests
1963
Saline Wet
1963
Semi-arid Wood (Shrubby)
1968
Semi-arid Wood (Grassy)
1956
WSF (Grassy)
1963
WSF (Shrubby)
1963
Log(Area (ha)+1)
Year
1900
1920
1940
1960
1980
2000
2020

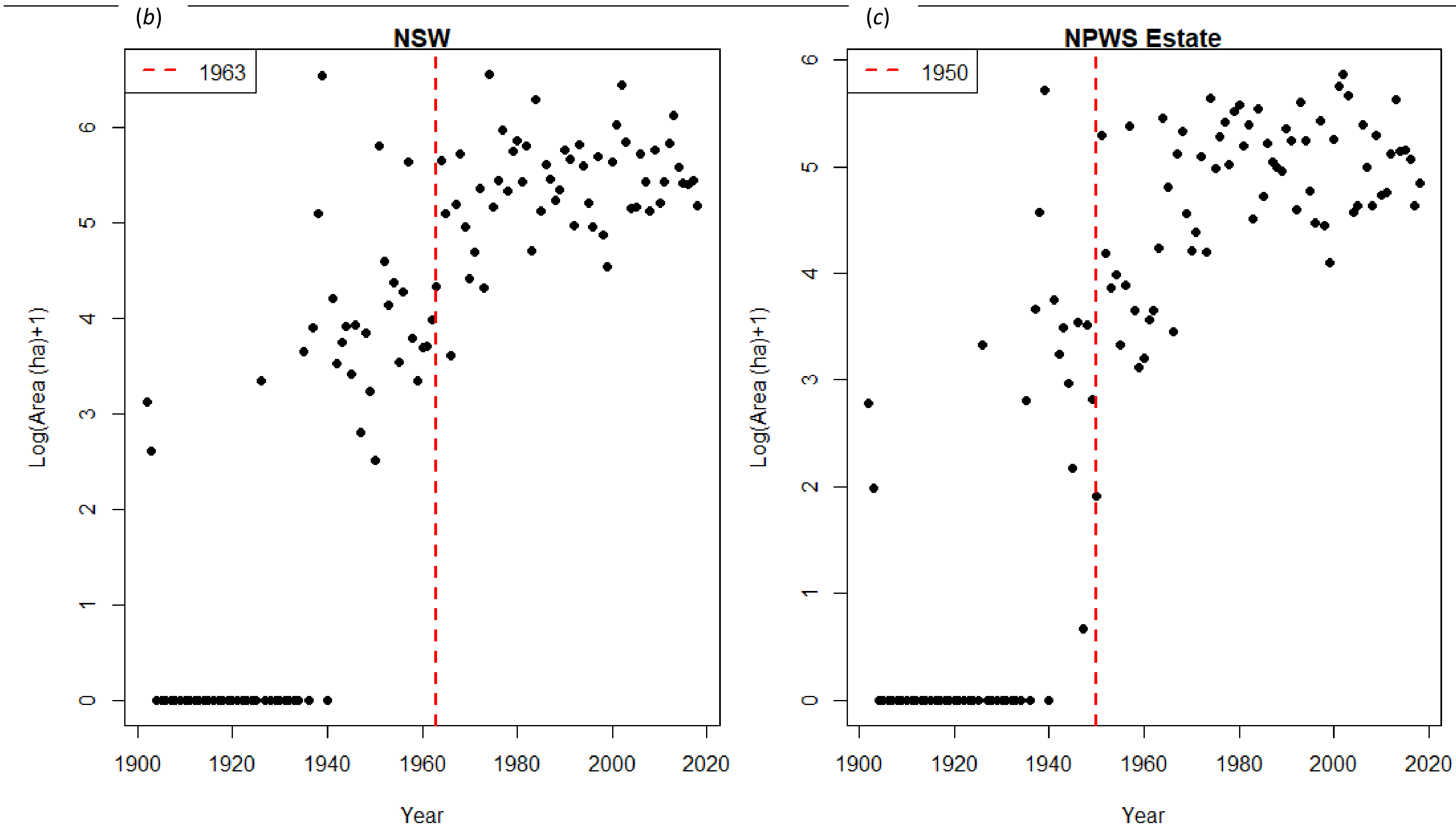
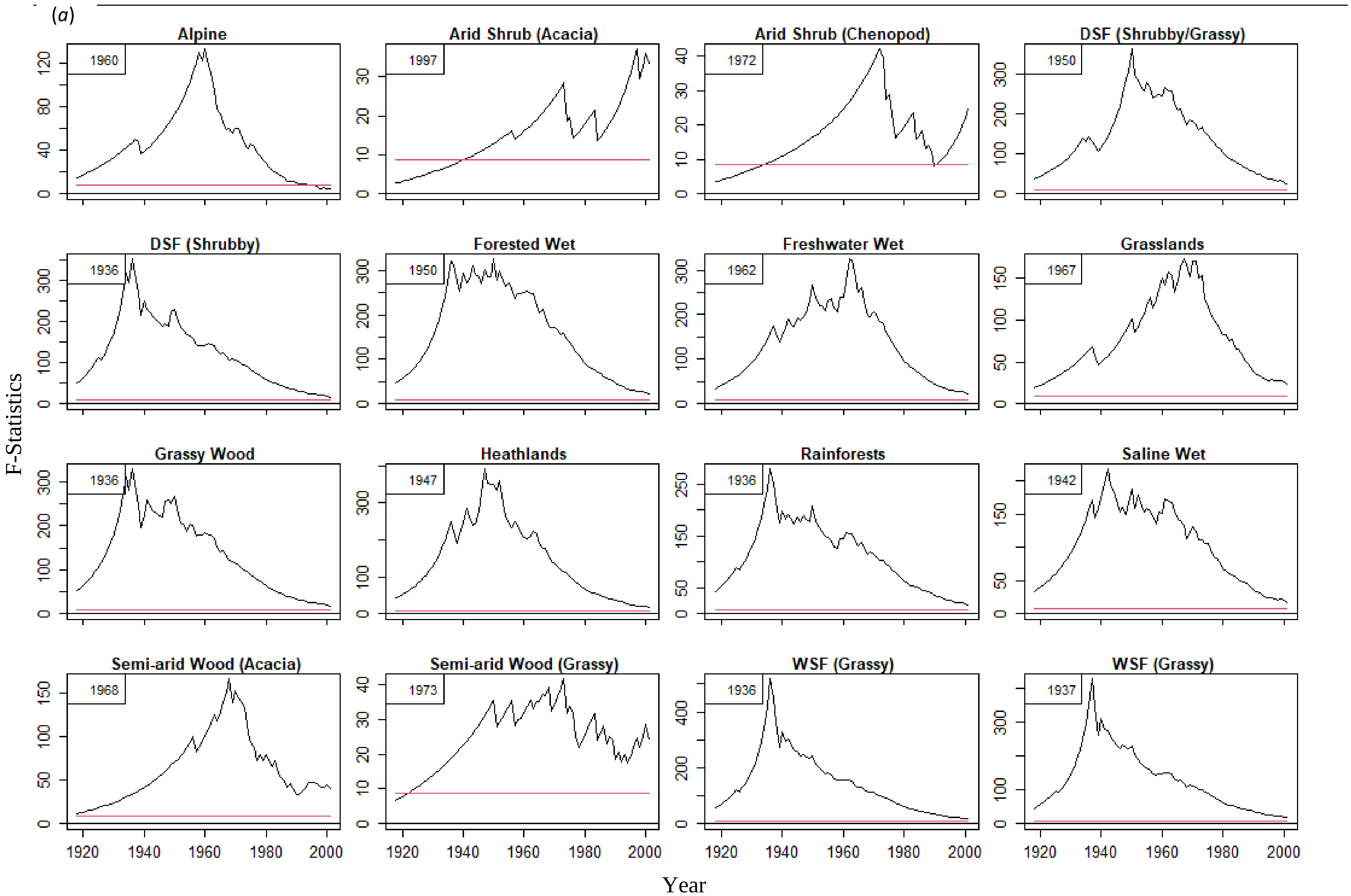


Figure A2. 1 Results of the non-parametric Pettit single change point test for area burnt recorded in the database between 1902 and 2018 for: (a) each vegetation formation; (b) NSW; and (c) NPWS Estate. All change points identified were statistically significant (P values between <0.0001 – 0.007). Change point indicated by dotted line. DSF, Dry Sclerophyll Forest; Shrub, Shrublands; Wet., Wetlands; Wood, Woodland; WSF, Wet Sclerophyll Forest


(a)
Alpine
1960
Arid Shrub (Acacia)
1997
Arid Shrub (Chenopod)
1972
DSF (Shrubby/Grassy)
1950
DSF (Shrubby)
1936
Forested Wet
1950
Freshwater Wet
1962
Grasslands
1967
Grassy Wood
1936
Heathlands
1947
Rainforests
1936
Saline Wet
1942
Semi-arid Wood (Acacia)
1968
Semi-arid Wood (Grassy)
1973
WSF (Grassy)
1936
WSF (Grassy)
1937
F-Statistics
Year
1920 1940 1960 1980 2000

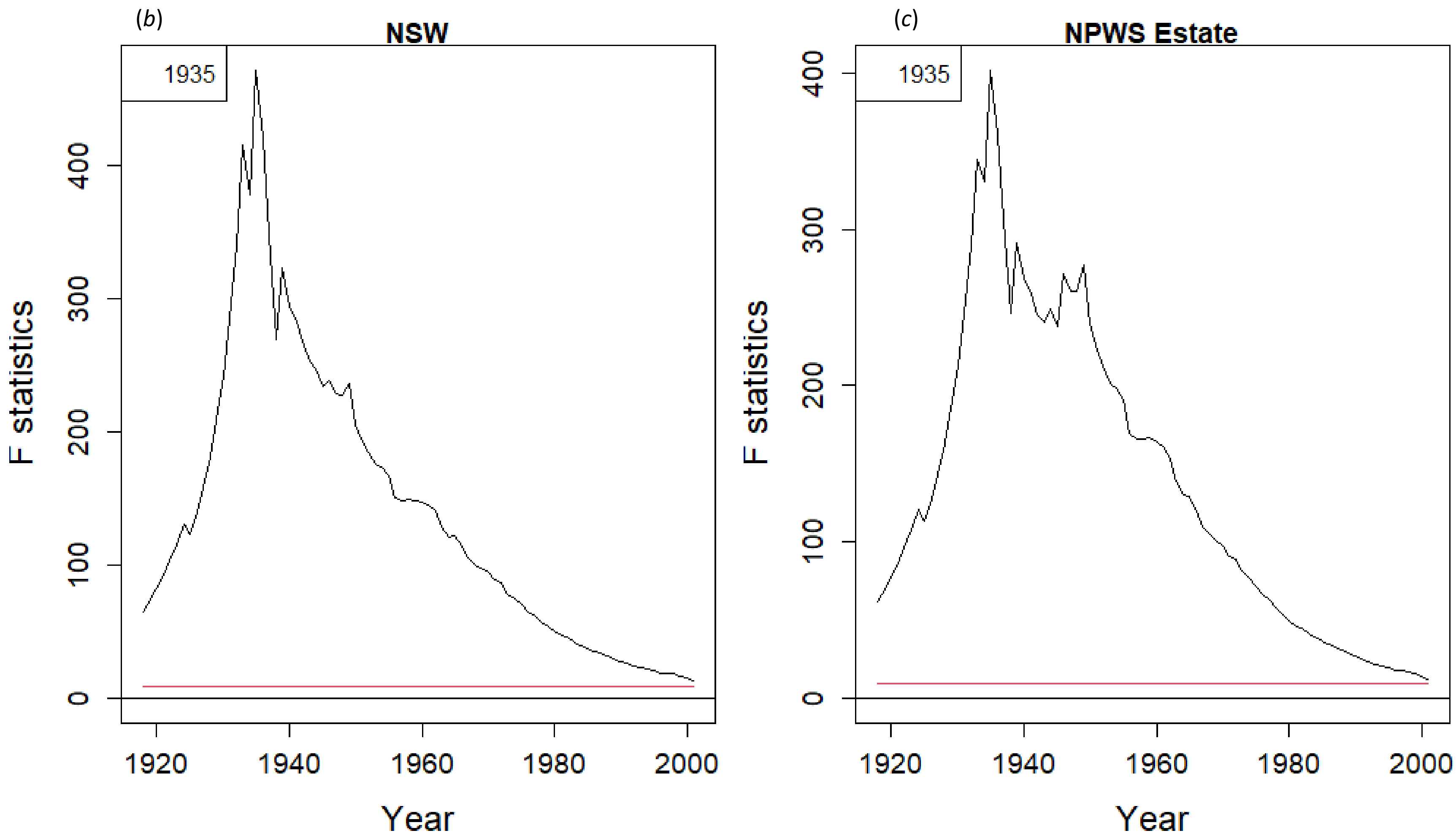
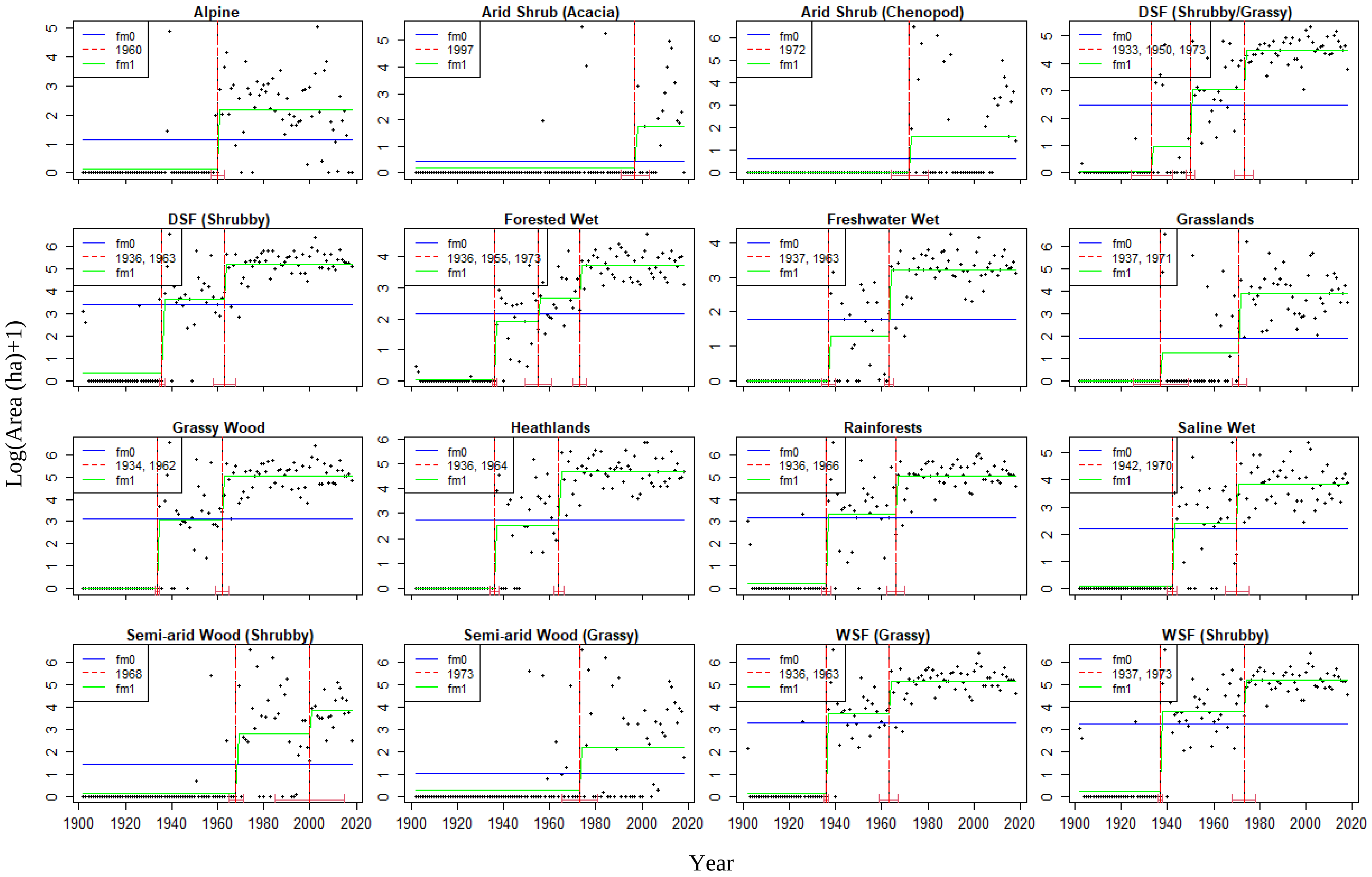


Figure A2. 2 Change points identified by the parametric F-Statistic single change point test for area burnt recorded in the database between 1902 and 2018 for: (a) each vegetation formation; (b) NSW; and (c) NPWS Estate. DSF, Dry Sclerophyll Forest; Shrub, Shrublands; Wet., Wetlands; Wood, Woodland; WSF, Wet Sclerophyll Forest

(*a*)



Alpine
fm0
1960
fm1
Arid Shrub (Acacia)
fm0
1997
fm1
Arid Shrub (Chenopod)
fm0
1972
fm1
DSF (Shrubby/Grassy)
fm0
1933, 1950, 1973
fm1
DSF (Shrubby)
fm0
1936, 1963
fm1
Forested Wet
fm0
1936, 1955, 1973
fm1
Freshwater Wet
fm0
1937, 1963
fm1
Grasslands
fm0
1937, 1971
fm1
Grassy Wood
fm0
1934, 1962
fm1
Heathlands
fm0
1936, 1964
fm1
Rainforests
fm0
1936, 1966
fm1
Saline Wet
fm0
1942, 1970
fm1
Semi-arid Wood (Shrubby)
fm0
1968
fm1
Semi-arid Wood (Grassy)
fm0
1973
fm1
WSF (Grassy)
fm0
1936, 1963
fm1
WSF (Shrubby)
fm0
1937, 1973
fm1
Log(Area (ha)+1)
Year
1900
1920
1940
1960
1980
2000
2020

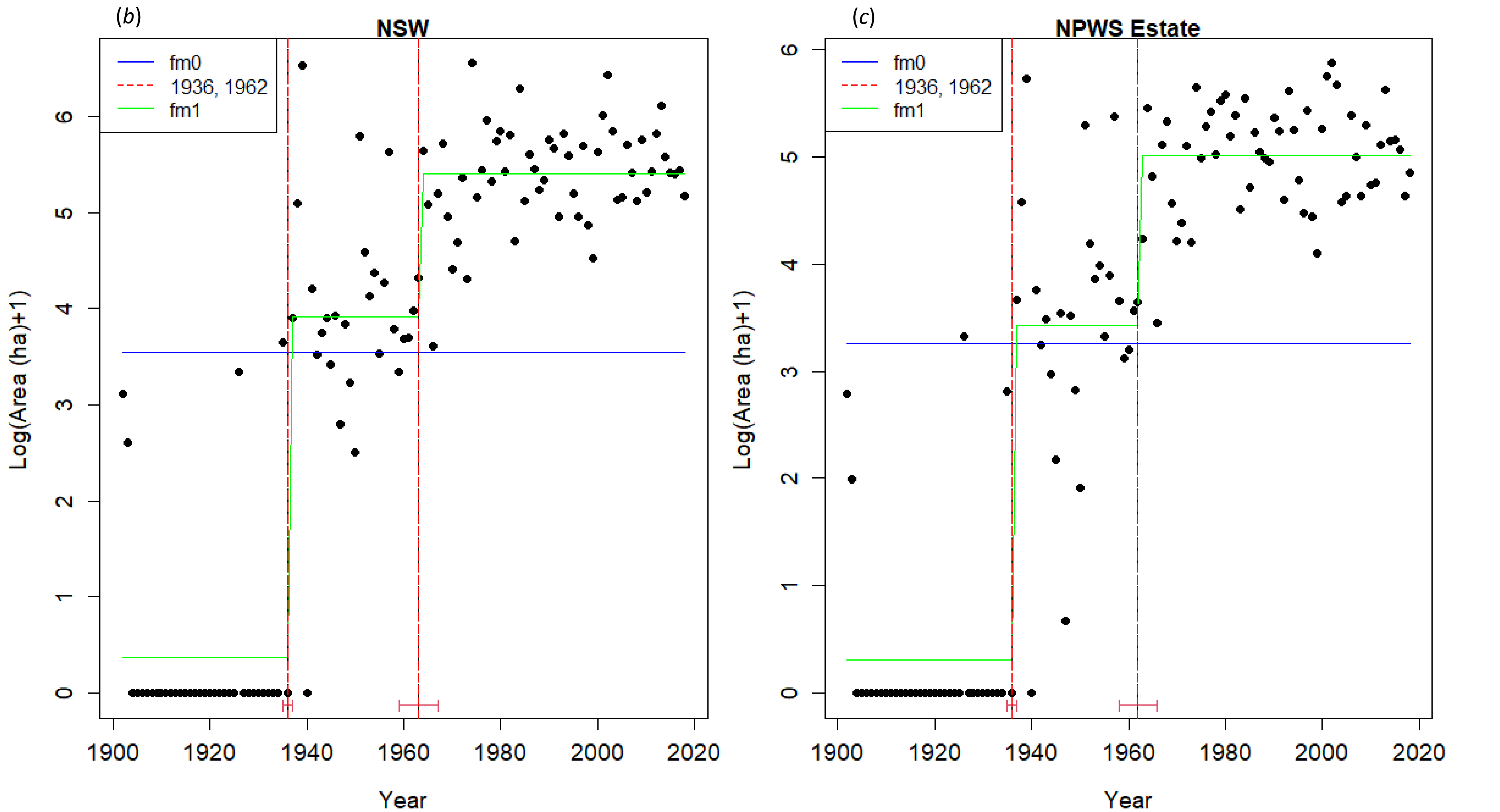
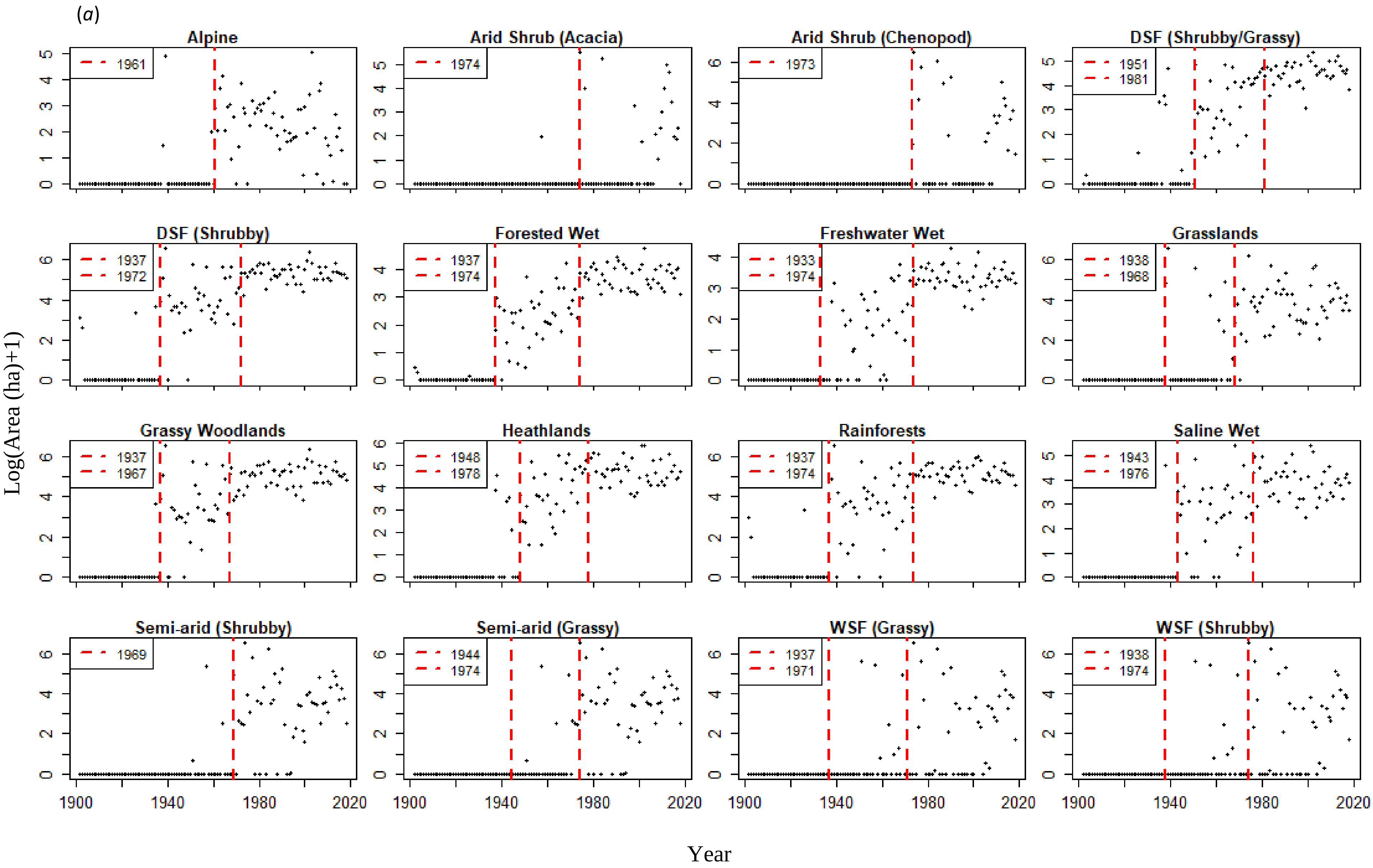


Figure A2. 3 Change points identified by the parametric Strucchange multiple change point test for area burnt recorded in the database between 1902 and 2018 for: (a) each vegetation formation; (b) NSW; and (c) NPWS Estate. Change points indicated by dotted lines; confidence intervals indicated by horizontal red line. DSF, Dry Sclerophyll Forest; Shrub, Shrublands; Wet., Wetlands; Wood, Woodland; WSF, Wet Sclerophyll Forest


(a)
Alpine
1961
Arid Shrub (Acacia)
1974
Arid Shrub (Chenopod)
1973
DSF (Shrubby/Grassy)
1951
1981
DSF (Shrubby)
1937
1972
Forested Wet
1937
1974
Freshwater Wet
1933
1974
Grasslands
1938
1968
Grassy Woodlands
1937
1967
Heathlands
1948
1978
Rainforests
1937
1974
Saline Wet
1943
1976
Semi-arid (Shrubby)
1969
Semi-arid (Grassy)
1944
1974
WSF (Grassy)
1937
1971
WSF (Shrubby)
1938
1974
Log(Area (ha)+1)
1900
1940
1980
2020
Year

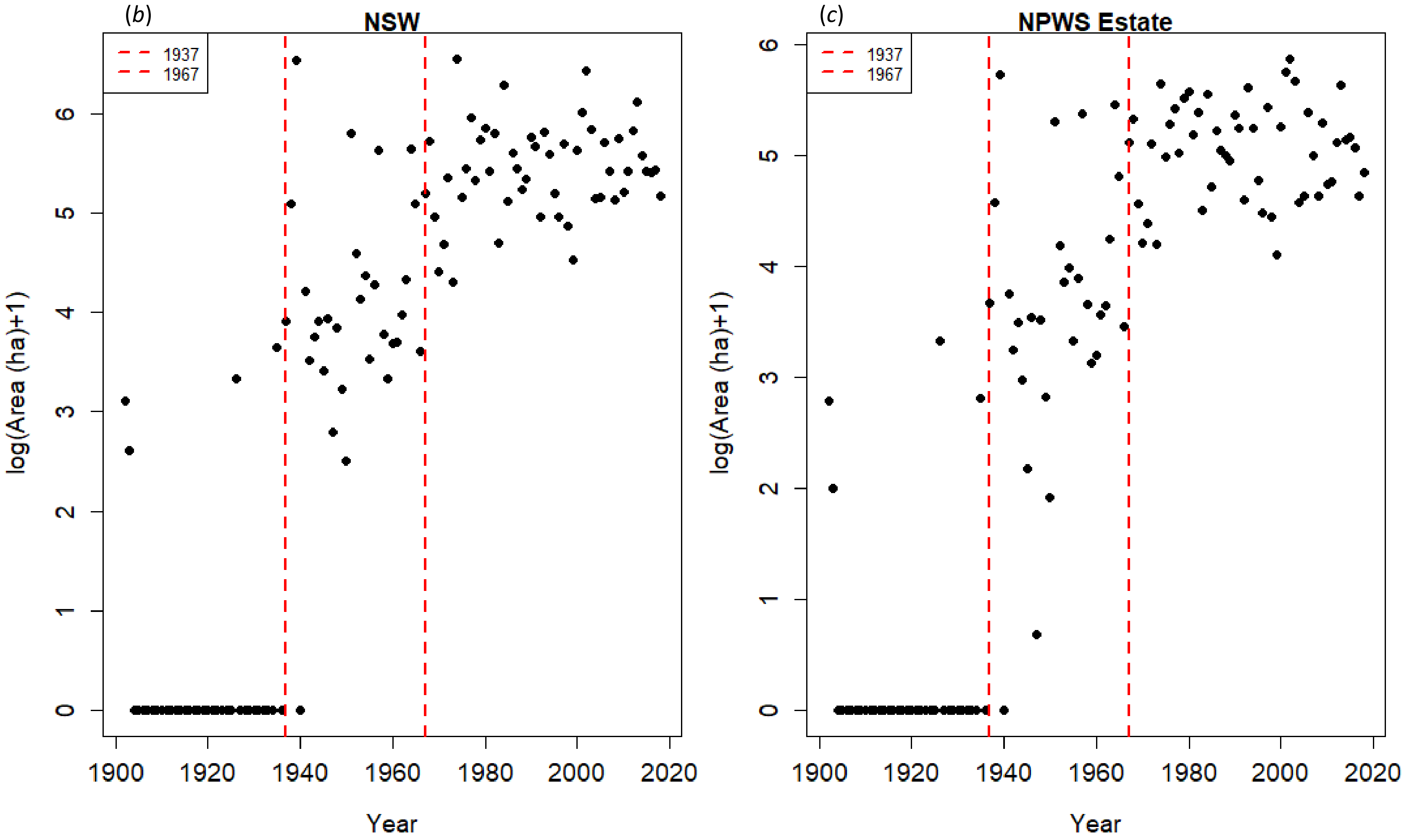
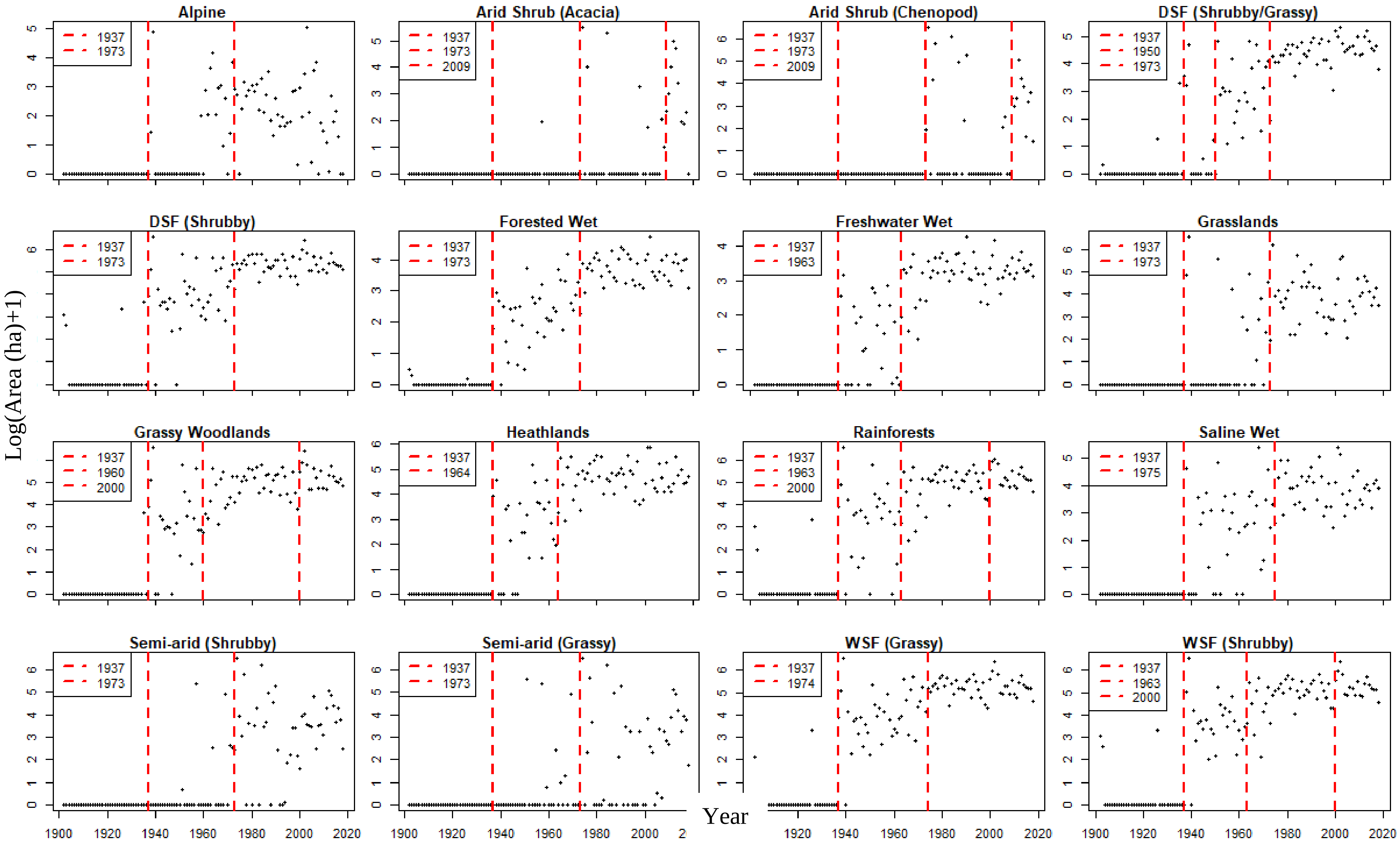


Figure A2. 4 Change points identified by the non-parametric E-Divisive multiple change point test of area burnt recorded in the database between 1902 and 2018 for: (a) each vegetation formation; (b) NSW; and (c) NPWS Estate. Change points indicated by dotted line. All change points identified were statistically significant (P values between 0.005 – 0.04). DSF, Dry Sclerophyll Forest; Shrub, Shrublands; Wet., Wetlands; Wood, Woodland; WSF, Wet Sclerophyll Forest

(*a*)


Alpine
Arid Shrub (Acacia)
Arid Shrub (Chenopod)
DSF (Shrubby/Grassy)
DSF (Shrubby)
Forested Wet
Freshwater Wet
Grasslands
Grassy Woodlands
Heathlands
Rainforests
Saline Wet
Semi-arid (Shrubby)
Semi-arid (Grassy)
WSF (Grassy)
WSF (Shrubby)
Log(Area (ha)+1)
Year

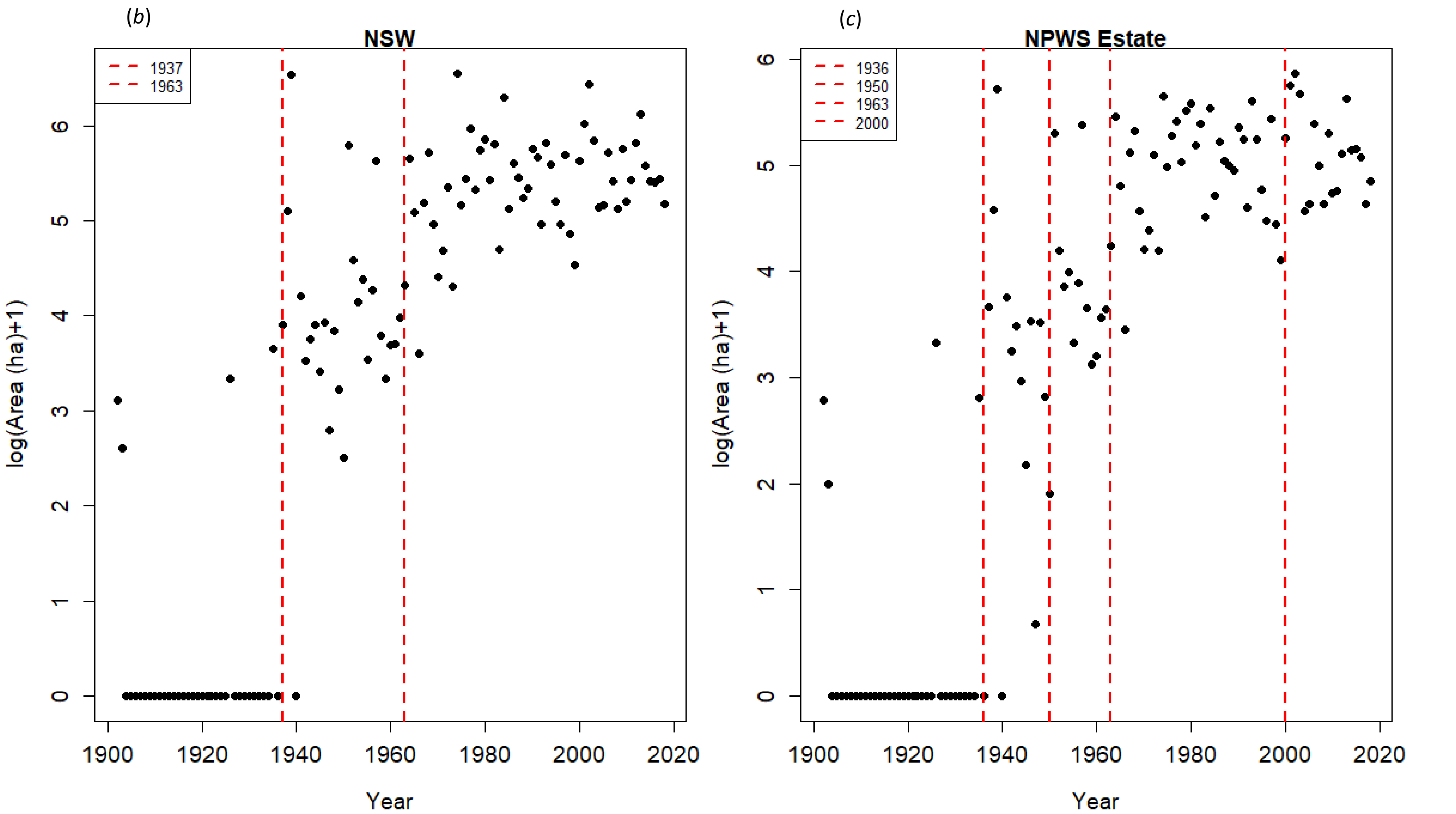
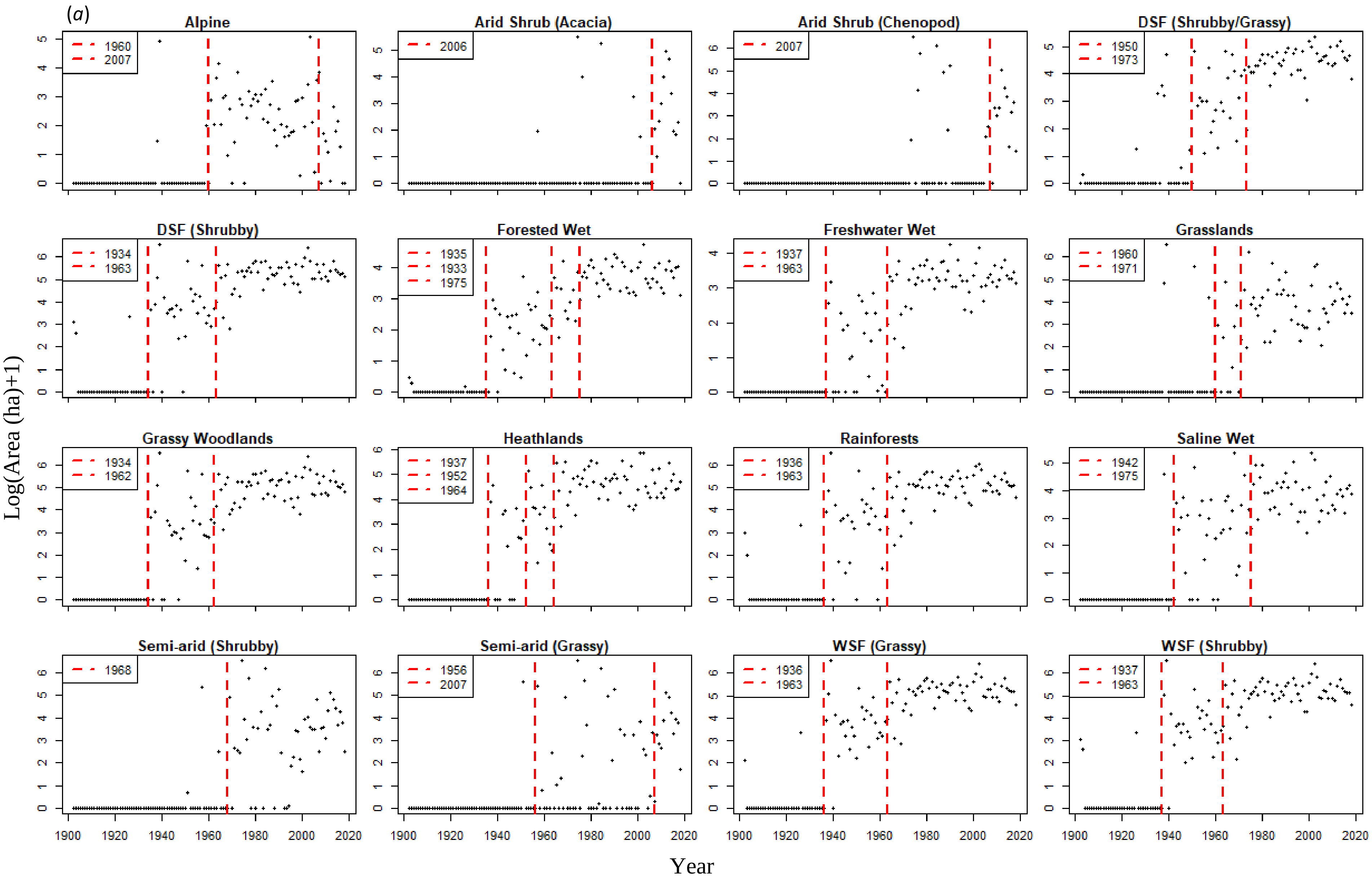


Figure A2. 5 Change points identified by the non-parametric Lepage multiple change point test for area burnt recorded in the database between 1902 and 2018 for: (a) each vegetation formation; (b) NSW; and (c) NPWS Estate. Change points indicated by dotted line. DSF, Dry Sclerophyll Forest; Shrub, Shrublands; Wet., Wetlands; Wood, Woodland; WSF, Wet Sclerophyll Forest


(a)
Alpine
1960
2007
Arid Shrub (Acacia)
2006
Arid Shrub (Chenopod)
2007
DSF (Shrubby/Grassy)
1950
1973
DSF (Shrubby)
1934
1963
Forested Wet
1935
1933
1975
Freshwater Wet
1937
1963
Grasslands
1960
1971
Grassy Woodlands
1934
1962
Heathlands
1937
1952
1964
Rainforests
1936
1963
Saline Wet
1942
1975
Semi-arid (Shrubby)
1968
Semi-arid (Grassy)
1956
2007
WSF (Grassy)
1936
1963
WSF (Shrubby)
1937
1963
Log(Area (ha)+1)
Year

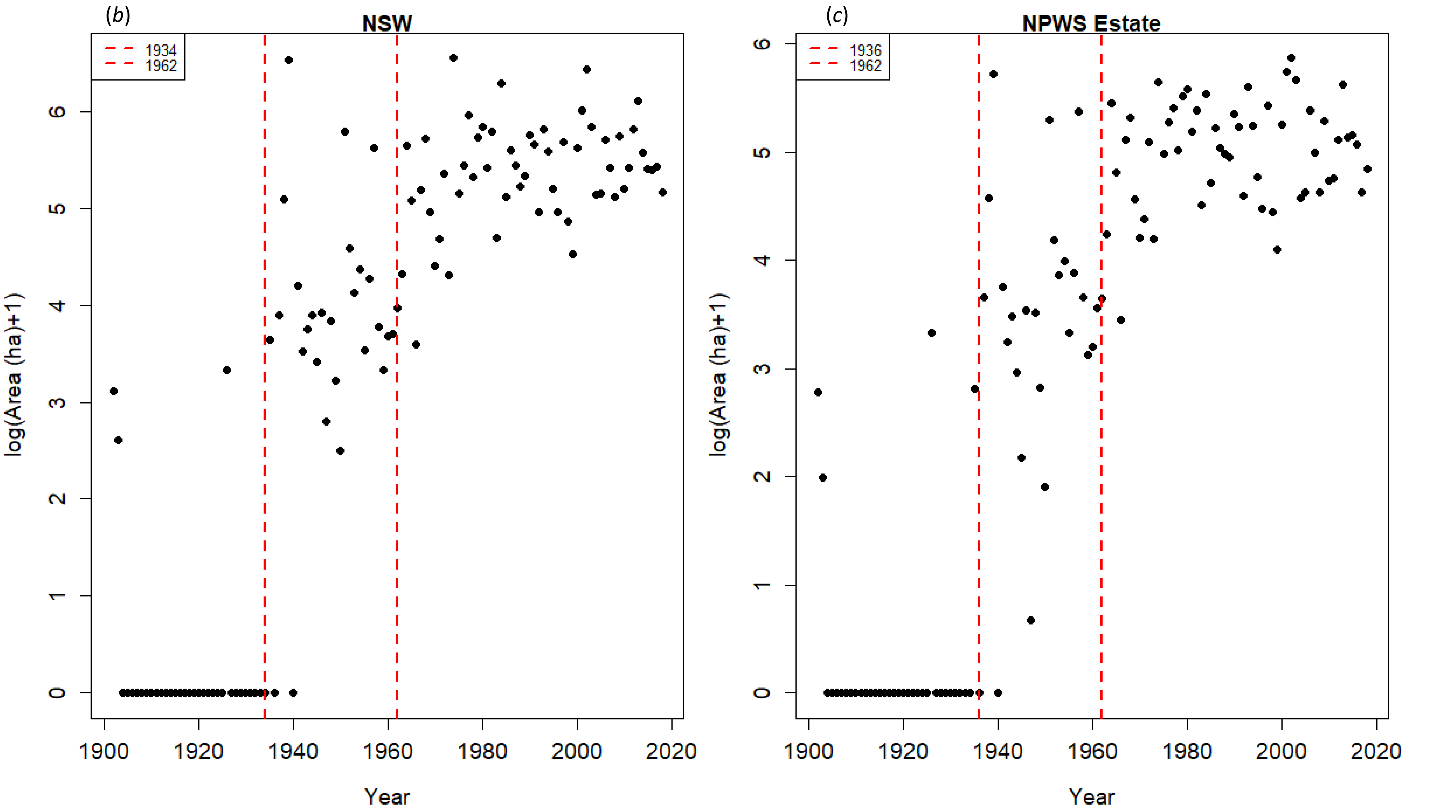
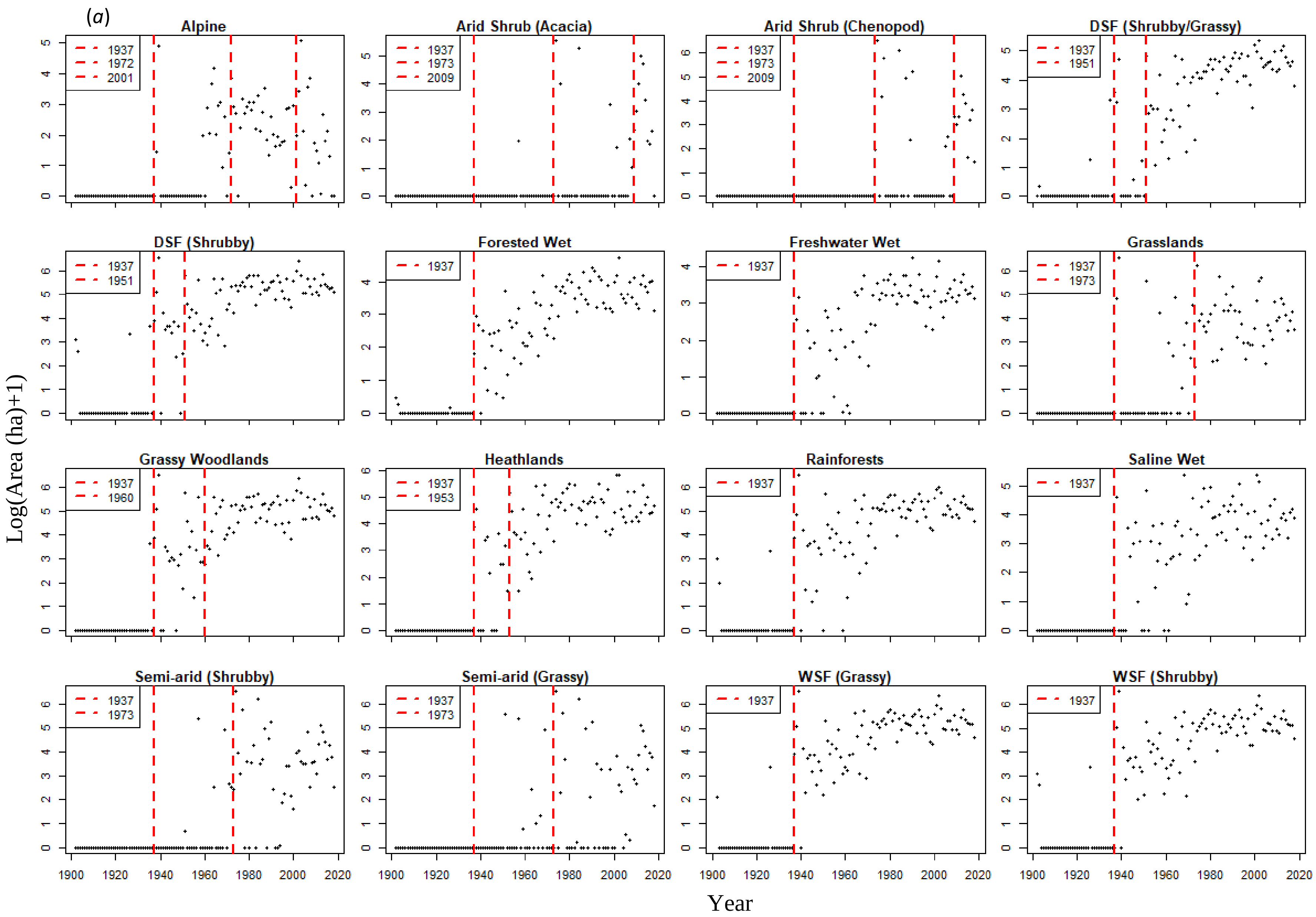


Figure A2. 6 Change points identified by the non-parametric Mann-Whitney multiple change point test for area burnt recorded in the database between 1902 and 2018 for: (a) each vegetation formation; (b) NSW; and (c) NPWS Estate. Change points indicated by dotted line. DSF, Dry Sclerophyll Forest; Shrub, Shrublands; Wet., Wetlands; Wood, Woodland; WSF, Wet Sclerophyll Forest


(a)
Alpine
1937
1972
2001
Arid Shrub (Acacia)
1937
1973
2009
Arid Shrub (Chenopod)
1937
1973
2009
DSF (Shrubby/Grassy)
1937
1951
DSF (Shrubby)
1937
1951
Forested Wet
1937
Freshwater Wet
1937
Grasslands
1937
1973
Grassy Woodlands
1937
1960
Heathlands
1937
1953
Rainforests
1937
Saline Wet
1937
Semi-arid (Shrubby)
1937
1973
Semi-arid (Grassy)
1937
1973
WSF (Grassy)
1937
WSF (Shrubby)
1937
Log(Area (ha)+1)
Year

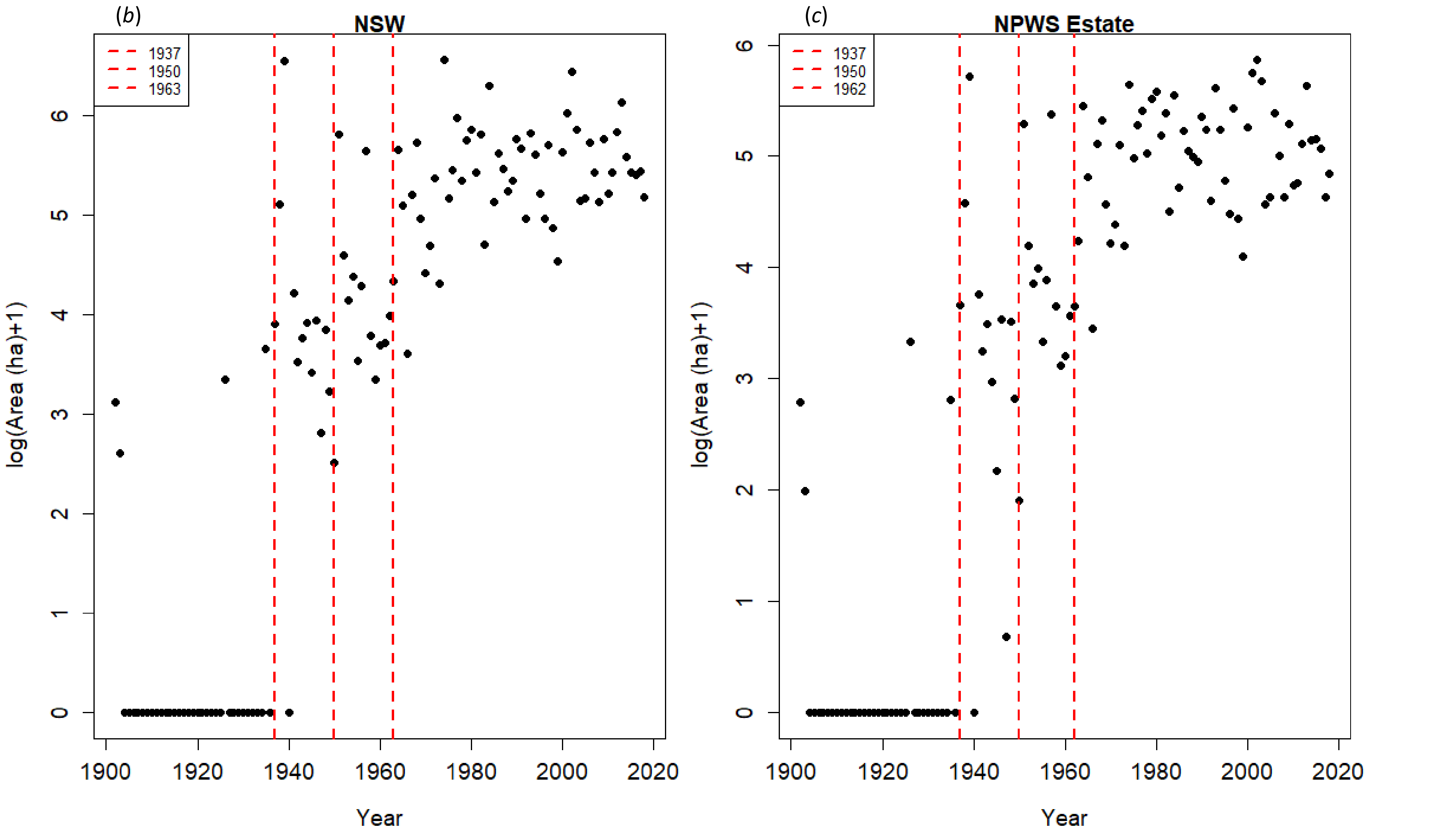


Figure A2. 7 Change points identified by the non-parametric Mood multiple change point test for area burnt recorded in the database between 1902 and 2018 for: (a) each vegetation formation; (b) NSW; and (c) NPWS Estate. Change points indicated by dotted line. DSF, Dry Sclerophyll Forest; Shrub, Shrublands; Wet., Wetlands; Wood, Woodland; WSF, Wet Sclerophyll Forest

Records of fires found in Trove newspaper archive not found in NSW fire database

To determine the completeness of the fire datasets, a search of the online electronic newspaper archive of the National Library of Australia (Trove) was conducted. All available electronic copies of 479 newspapers published in NSW between 1803 and 2009, using the search term ‘bush fire’ were searched to find potential articles. The criteria for inclusions were that fire occurred within 10 km of vegetation that was extant in 2018 (including on private property), and at least five hectares (or described as large, as not all articles cited fire size). A more systematic search was undertaken for the two vegetation formations in western NSW where newspapers of towns that were settled in the 19th Century were searched for reports of fires between 1800 and 1969. The first 100 articles per year (or all articles if fewer than 100 per year) from 1803 to 2009 were searched. If the fire occurred within an area that is currently zoned as NSW National Parks and Wildlife Service (NSW NPWS) Estate, the name of the National Park was noted (Table S3).

Table A2. 1 Newspaper, year of publication and fire, location, vegetation formation and NPWS Estate of fires found in Trove from 1803 - 1969 not found in the database. NP = National Park; NR = Nature Reserve; RP = Regional Park; SCA = State Conservation Area

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Sydney Monitor	1836	Macleay River	Wet Sclerophyll (Shrubby & Grassy)/Dry Sclerophyll (Grassy)/Rainforests	
The Sydney Monitor	1837	Brisbane Waters	Dry Sclerophyll (Shrubby)/Saline Wetlands/Heathlands/Wet Sclerophyll (Grassy)/Freshwater Wetlands	Brisbane Waters NP
The Sydney Herald	1839	Murray River	Semi-arid Woodlands (Shrubby)/Grassy Woodlands/Freshwater Wetlands	Murray Valley NP

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
The Sydney Herald	1842	Bathurst	Dry Sclerophyll (Shrubby)	Winburndale NR
Sydney Morning Herald	1842	Goulburn	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The Sydney Morning Herald	1842	Kempsey	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby & Grassy)	
The Sentinel	1845	Wollombi District	Dry Sclerophyll (Grassy)	Yengo NP
Morning Chronicle	1845	Maitland	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby & Grassy))	
The Sydney Morning Herald	1846	Lower Murrumbidgee	Forested Wetlands	Murrumbidgee Valley NP/Murrumbidgee Valley SCA
The Sydney Morning Herald	1847	Maroota	Dry Sclerophyll (Shrubby)	Marramarra NP
The Maitland Mercury and Hunter General River Advertiser	1847	Singleton District	Dry Sclerophyll (Shrubby)	
The Australian	1847	Jerrys Plains	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Wollemi NP
Sydney Chronicle	1847	Hartley	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby)	
Sydney Chronicle	1848	Wollombi District	Dry Sclerophyll (Grassy)	Yengo NP
The Maitland Mercury and Hunter River General Advertiser	1848	Tabulam	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	
The Australian	1848	Dungog	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	
The Maitland Mercury and Hunter River General Advertiser	1849	Wollombi District	Dry Sclerophyll (Grassy)	Yengo NP
The Sydney Morning Herald	1849	Berrima District	Dry Sclerophyll (Shrubby & Grassy)/Wet Sclerophyll (Shrubby)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Sydney Morning Herald	1849	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Goulburn Herald and County of Argyle Advertiser	1851	Port Philip (Most of NSW)	All	
The Sydney Morning Herald	1851	Berrima District	Dry Sclerophyll (Shrubby & Grassy)/Wet Sclerophyll (Grassy)	
The Sydney Morning Herald	1851	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The People's Advocate and New South Wales Vindicator	1851	Portland District	Dry Sclerophyll (Shrubby)/Grassy Woodlands	
The Sydney Morning Herald	1853	Wollombi District	Dry Sclerophyll (Grassy)	Yengo NP
The Maitland Mercury and Hunter General River Advertiser	1853	Singleton District	Dry Sclerophyll (Shrubby)	
The Goulburn Herald and County of Argyle Advertiser	1853	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The Sydney Morning Herald	1853	Dungog District	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	
The Sydney Morning Herald	1853	Cassilis District	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby)	Durridgere SCA
The Sydney Morning Herald	1854	Appin	Dry Sclerophyll (Shrubby)	Dharawal NP
Empire	1854	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The Sydney Morning Herald	1854	Wollongong to Botany Heads	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
Sydney Morning Herald	1855	Yass	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Mundoonen NR
Freeman's Journal	1855	Portland District	Dry Sclerophyll (Shrubby)/Grassy Woodlands	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Sydney Morning Herald	1855	Mount Kembla/Wollongong District	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
Bathurst Free Press and Mining Journal	1856	Wollombi District	Dry Sclerophyll (Grassy)	Yengo NP
The Goulburn Herald and County of Argyle Advertiser	1857	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
The Sydney Morning Herald	1857	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The Sydney Morning Herald	1857	Albury District	Freshwater Wetlands/Dry Sclerophyll (Grassy)	
Empire	1857	Burrendong	Grassy Woodlands/Dry Sclerophyll (Grassy)	
The Sydney Morning Herald	1858	Peel River	Dry Sclerophyll (Grassy)	
Empire	1858	Goulburn	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Sydney Morning Herald	1858	Yass	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Mundoonen NR
Empire	1858	Tambaroora	Dry Sclerophyll (Shrubby)/Grassy Woodlands	
Empire	1858	Black Range	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Grassy Woodlands/Rainforests/Forested Wetlands	Bournda NR
The Sydney Morning Herald	1858	Mount Rankin	Grassy Woodlands/Dry Sclerophyll (Grassy)/Freshwater Wetlands	
The Maitland Mercury and Hunter River General Advertiser	1858	Port Macquarie District	Wet Sclerophyll (Grassy & Shrubby)/Forested Wetlands/Saline Wetlands	Woregore NR/Lake Innes NR/Macquarie NR

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
The Maitland Mercury and Hunter River General Advertiser	1858	Mangrove Creek	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby)/Heathlands	Dharug NP/Popran NP
The Armidale Express and New England Advertiser	1859	Tamworth District	Dry Sclerophyll (Grassy)	
The Sydney Morning Herald	1859	Wellington	Dry Sclerophyll (Grassy)/Grassy Woodlands	
The Maitland Mercury and Hunter River General Advertiser	1859	Fordwich	Dry Sclerophyll (Shrubby & Grassy)	Yengo NP/Wollemi NP
The Sydney Morning Herald	1859	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Goulburn Herald	1860	Wheeo	Dry Sclerophyll (Shrubby)	
The Sydney Morning Herald	1860	Yass	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Mundoonen NR
Goulburn Herald	1860	Black Range	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Grassy Woodlands/Rainforests/Forested Wetlands	Bournda NR
Sydney Mail	1861	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
The Sydney Morning Herald	1861	Pomingalarma Range, Wagga Wagga	Dry Sclerophyll (Grassy)/Grassy Woodlands	
Bathurst Free Press and Mining Journal	1861	Wellington	Dry Sclerophyll (Grassy)/Grassy Woodlands	
The Maitland Mercury and Hunter River General Advertiser	1861	Moonby Range	Grassy Woodlands/Dry Sclerophyll (Shrubby & Grassy)	
The Maitland Mercury and Hunter River General Advertiser	1862	Mudgee	Dry Sclerophyll (Grassy & Shrubby)	Avisford NR
Maitland Mercury and Hunter River General Advertiser	1862	Howe’s Valley	Dry Sclerophyll (Grassy & Shrubby) / Grassy Woodlands	Yengo NP/Wollemi NP

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Maitland Mercury and Hunter River General Advertiser	1862	Scone	Dry Sclerophyll (Grassy) / Grassy Woodlands	Scone Mountain NP
Empire	1862	Appin	Dry Sclerophyll (Shrubby)	Dharawal NP
The Maitland Mercury and Hunter River General Advertiser	1862	Howe's Valley	Dry Sclerophyll (Shrubby)	Yengo NP/Wollemi NP
Empire	1862	North Head and Middle Harbour	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
The Maitland Mercury and Hunter River General Advertiser	1862	Illawarra Mountain Ranges	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
The Newcastle Chronicle and Hunter River District News	1862	Port Stephens	Forested Wetlands/Dry Sclerophyll (Shrubby)/Saline Wetlands	Tomaree NP/Tilligerry NR
The Maitland Mercury and Hunter River General Advertiser	1862	Moonby Range	Grassy Woodlands/Dry Sclerophyll (Shrubby & Grassy)	
Sydney Mail	1862	Braidwood District	Wet Sclerophyll (Shrubby)/Dry Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
The Monaro Mercury, and Cooma and Bombala Advertiser	1863	Snowy Plains	Grassy Woodlands/Alpine	Kosciuszko NP
The Maitland Mercury and Hunter River General Advertiser	1865	Mudgee District	Dry Sclerophyll (Grassy & Shrubby)	Avisford NR
The Tumut and Adelong Times	1865	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
The Maitland Mercury and Hunter River General Advertiser	1865	Raymond Terrace	Dry Sclerophyll (Grassy & Shrubby)/Wet Sclerophyll (Grassy)	Tilligerry SCA
The Maitland Mercury and Hunter River General Advertiser	1865	Bowling Alley Point	Dry Sclerophyll (Shrubby & Grassy)/Wet Sclerophyll (Grassy)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Goulburn Herald and Chronicle	1865	Araluen	Dry Sclerophyll (Shrubby & Grassy)/Wet Sclerophyll (Shrubby)	Mongo NP
The Sydney Morning Herald	1865	Lower Murrumbidgee	Forested Wetlands	Murrumbidgee Valley NP/Murrumbidgee Valley SCA
Sydney Morning Herald	1865	Murrumbidgee	Forested Wetlands	Murrumbidgee Valley NP/Murrumbidgee Valley SCA
Freeman's Journal	1865	Albury	Freshwater Wetlands/Dry Sclerophyll (Grassy)	
The Sydney Morning Herald	1865	Deniliquin	Semi-arid Woodlands (Shrubby)/Grassy Woodlands/Freshwater Wetlands	Murray Valley NP
The Sydney Morning Herald	1866	Bega	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	Mimosa Rocks NP
Sydney Mail	1866	Sutton Forest	Dry Sclerophyll (Shrubby & Grassy)/Wet Sclerophyll (Grassy)	Moreton NP
The Tumut and Adelong Times	1866	Adelong	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
Empire	1867	North of the Wollondilly River	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	Cookbundoon NR
The Sydney Morning Herald	1867	Dungog	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	
The Bega Gazette and Eden District or Southern Coast Advertiser	1868	Bega District	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	Mimosa Rocks NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Maitland Mercury and Hunter River General Advertiser	1868	Armidale Region	Dry Sclerophyll (Shrubby & Grassy)	Yina NR
The Sydney Morning Herald	1868	Emu Creek	Dry Sclerophyll (Shrubby & Grassy)	
The Newcastle Chronicle	1868	Wallsend Region	Dry Sclerophyll (Shrubby & Grassy)	Blue Gum Hills RP
Goulburn Herald and Chronicle	1868	Goulburn	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Queanbeyan Age	1868	Queanbeyan	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Queanbeyan NR/Cuumbeun NR
The Sydney Morning Herald	1868	Yass	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Mundoonen NR
The Gundagai Times and Tumut, Adelong and Murrumbidgee District Advertiser	1868	Adelong	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
Empire	1868	Ulladulla District	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	
The Sydney Morning Herald	1868	Araluen	Dry Sclerophyll (Shrubby & Grassy)/Wet Sclerophyll (Shrubby)	Mongo NP
The Goulburn Herald and Chronicle	1868	Tuena	Grassy Woodlands/Dry Sclerophyll (Shrubby)	Razorback NR
The Kiama Independent, and Shoalhaven Advertiser	1868	Cambewarra	Wet Sclerophyll (Shrubby)/Rainforests	Cambewarra Range NR
Gundagai Times	1869	Upper Adelong	Dry Sclerophyll (Grassy) / Grassy Woodlands	
Empire	1869	Twofold Bay	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Ben Boyd NP
Maitland Mercury and Hunter River General Advertiser	1870	Wollombi range	Dry Sclerophyll (Shrubby)	Yengo NP

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Maitland Mercury and Hunter River General Advertiser	1870	East Kempsey	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Grassy)	
The Maitland Mercury and Hunter River General Advertiser	1871	Denman	Dry Sclerophyll (Grassy & Shrubby)	
Australian Town and Country Journal	1871	Grenfell	Dry Sclerophyll (Shrubby)	Weddin Mountains NP/Conimbla NP
Wagga Wagga Advertiser and Riverine Reporter	1871	Narandera	Forested Wetlands / Grassy Woodlands / Semi-arid Woodlands (Shrubby)	Murrumbidgee Valley NR
Australian Town and Country Journal	1871	Sofala	Forested Wetlands/Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
The Maitland Mercury and Hunter River General Advertiser	1871	Murrurundi	Grassy Woodlands/Wet Sclerophyll (Grassy)	Murrurundi Pass NP
The Maitland Mercury and Hunter River General Advertiser	1871	Brewarrina	Semi-arid Woodlands (Shrubby & Grassy)/Grasslands	
The Maitland Mercury and Hunter River General advertiser	1871	Kempsey	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby & Grassy)	
The Maitland Mercury and Hunter River General Advertiser	1872	Boggabri	Dry Sclerophyll (Shrubby & Grassy)/Grasslands	
Australian Town and Country Journal	1872	Braidwood	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Wagga Wagga Express and Murrumbidgee District Advertiser	1872	Gillenbah	Forested Wetlands	Murrumbidgee Valley NP
The Maitland Mercury and Hunter River General Advertiser	1872	Gunnedah	Grassy Woodlands	

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Australian Town and Country Journal	1872	Bombala	Grassy Woodlands/Dry Sclerophyll (Shrubby & Grassy)/Wet Sclerophyll (Shrubby)	Coolumbooka NR
Wagga Wagga Advertiser and Riverine Reporter	1873	Pomingalarna Ranges	Dry Sclerophyll (Grassy)/Grassy Woodlands	
Evening News	1873	Grenfell	Dry Sclerophyll (Shrubby)	Weddin Mountains NP/Conimbla NP
Empire	1873	Murrumbidgee District	Forested Wetlands	Murrumbidgee Valley NP/Murrumbidgee Valley SCA
The Maitland Mercury and Hunter River General Advertiser	1874	Goorangoola	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	
The Singleton Argus and Upper Hunter General Advocate	1874	Glendon Brook	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)/Rainforests	
Goulburn Herald and Chronicle	1874	Gundaroo	Dry Sclerophyll (Shrubby) / Grassy Woodlands	McLeod’s Creek NR
Evening News	1874	Queanbeyan	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Queanbeyan NR/Cuumbeun NR
The Monaro Mercury, and Cooma and Bombala Advertiser	1874	Wambrook	Dry Sclerophyll (Shrubby)/Grassy Woodlands/Grasslands	Binjura NR
The Maitland Mercury and Hunter River General Advertiser	1874	Scone District	Grassy Woodlands/Dry Sclerophyll (Grassy)	Scone Mountain NP
The Maitland Mercury and Hunter River General Advertiser	1875	Wollombi District	Dry Sclerophyll (Grassy)	Yengo NP
Australian Town and Country Journal	1875	Bega	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	Mimosa Rocks NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Maitland Mercury and Hunter River General Advertiser	1875	Warialda	Dry Sclerophyll (Shrubby & Grassy)	Warialda SCA
Queanbeyan Age	1875	Gundaroo	Dry Sclerophyll (Shrubby) / Grassy Woodlands	McLeod's Creek NR
The Maitland Mercury and Hunter River General Advertiser	1875	Inverell	Dry Sclerophyll (Shrubby)/Heathlands	Barayamal NP/Goonoowigal NP
The Sydney Mail and New South Wales Advertiser	1875	Blue Mountains	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Blue Mountains NP
The Cumberland Mercury	1875	Blue Mountains	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Blue Mountains NP
Australian Town and Country Journal	1875	Braidwood	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Australian Town and Country Journal	1875	Ulladulla	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	
Australian Town and Country Journal	1875	Shoalhaven District	Wet Sclerophyll (Grassy & Shrubby)/Heathlands/Dry Sclerophyll (Shrubby)	Jerrawangala NP/Conjola NP
The Gundagai Times and Tumut, Adelong and Murrumbidgee District Advertiser	1876	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
Evening News	1876	Grafton	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands/Wet Sclerophyll (Shrubby)	
The Newcastle Chronicle	1876	Raymond Terrace	Dry Sclerophyll (Grassy & Shrubby)/Wet Sclerophyll (Grassy)	Tilligerry SCA
The Maitland Mercury and Hunter River General Advertiser	1876	Bulga Mountain	Dry Sclerophyll (Shrubby & Grassy)	Wollemi NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Miner's Advocate and Northumberland Recorder	1876	Wallsend	Dry Sclerophyll (Shrubby & Grassy)	Blue Gum Hills RP
Newcastle Morning Herald and Miner's Advocate	1877	Braidwood	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Evening News	1878	Grafton	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands/Wet Sclerophyll (Shrubby)	
The Maitland Mercury and Hunter River General Advertiser	1878	Hill End	Dry Sclerophyll (Shrubby & Grassy)/Grassy Woodlands	
Goulburn Herald and Chronicle	1878	Goulburn	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Evening News	1878	North Head	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
The Kiama Independent, and Shoalhaven Advertiser	1878	Mountains behind Wollongong	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
The Sydney Morning Herald	1878	Albury Region	Freshwater Wetlands/Dry Sclerophyll (Grassy)	
The Kiama Independent, and Shoalhaven Advertiser	1878	Kangaroo Valley	Wet Sclerophyll (Grassy & Shrubby)/Rainforests/Dry Sclerophyll (Shrubby)	Kangaroo River NR
The Maitland Mercury and Hunter River General advertiser	1879	Denman	Dry Sclerophyll (Grassy & Shrubby)	
The Maitland Mercury and Hunter River General Advertiser	1879	Jerrys Plains	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Wollemi NP
The Maitland Mercury and Hunter River General Advertiser	1879	Murrurundi	Grassy Woodlands/Wet Sclerophyll (Grassy)	Murrurundi Pass NP
The Gundagai Times and Tumut, Adelong and	1880	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Murrumbidgee District Advertiser				
Newcastle Morning Herald and Miner's Advocate	1880	Wallsend	Dry Sclerophyll (Shrubby & Grassy)	Blue Gum Hills RP
The Maitland Mercury and Hunter River General Advertiser	1880	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Queanbeyan Age	1880	Queanbeyan	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Queanbeyan NR/Cuumbeun NR
Evening News	1880	Cobar	Semi-arid Woodlands (Shrubby & Grassy)/Arid Shrublands (Acacia)	
Newcastle Morning Herald and Miner's Advocate	1881	Aberdeen	Dry Sclerophyll (Grassy)/Grassy Woodlands	
The Sydney Morning Herald	1881	Toogong	Dry Sclerophyll (Shrubby)	South West Woodland NR
The Monaro Mercury, and Cooma and Bombala Advertiser	1881	Bunyan	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Binjura NR
The Sydney Mail and New South Wales Advertiser	1881	Yass	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Mundoonen NR
The Sydney Mail and New South Wales Advertiser	1881	Hanging Rock	Grassy Woodlands/Wet Sclerophyll (Grassy)/Dry Sclerophyll (Grassy)	
The Gundagai Times and Tumut, Adelong and Murrumbidgee District Advertiser	1882	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
Newcastle Morning Herald and Miner's Advocate	1882	Teralba	Dry Sclerophyll (Shrubby & Grassy)/Forested Wetlands	
Goulburn Herald	1882	Collector	Dry Sclerophyll (Shrubby)	
Evening News	1882	Goulburn	Dry Sclerophyll (Shrubby) / Grassy Woodlands	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Evening News	1882	Lithgow	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)/Heathlands	
Evening News	1882	Canobolas Ranges (seen form Blayney)	Grassy Woodlands/Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	Mount Canobolas SCA
The Sydney Daily Telegraph	1883	North Head	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
Newcastle Morning Herald and Miner's Advocate	1883	Moruya	Wet Sclerophyll (Grassy & Shrubby)/Dry Sclerophyll (Shrubby)/Grassy Woodlands	Eurobodalla NP
Evening News	1884	Capertee	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Gardens of Stone NP/Turon NP
Maitland Mercury and Hunter River General Advertiser	1884	Paterson	Dry Sclerophyll (Grassy)	
Bowral Free Press and Mittagong, Burrawang and Kangaloon Advocate	1884	Bowral and Mittagong Regions	Dry Sclerophyll (Grassy) / Grassy Woodlands	
Evening News	1884	Appin	Dry Sclerophyll (Shrubby)	Dharawal NP
Newcastle Morning Herald and Miner's Advocate	1884	Yass and Cootamundra	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Mundoonen NR
The Maitland Mercury and Hunter River General Advertiser	1884	Port Macquarie District	Wet Sclerophyll (Grassy & Shrubby)/Forested Wetlands/Saline Wetlands	Woregore NR/Lake Innes NR/Macquarie NR
Bowral Free Press and Berrima District Intelligencer	1885	Mountains between Bowral and Mittagong	Dry Sclerophyll (Grassy) / Grassy Woodlands	
Goulburn Evening Penny	1885	Black Ranges	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Grassy Woodlands/Rainforests/Forested Wetlands	Bournda NR
The Armidale Express and New England General Advertiser	1885	Glen Innes	Grassy Woodlands/Dry Sclerophyll (Shrubby)	

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Newcastle Morning Herald and Miner’s Advocate	1885	Moruya	Wet Sclerophyll (Grassy & Shrubby)/Dry Sclerophyll (Shrubby)/Grassy Woodlands	Eurobodalla NP
Corowa Free Press	1886	Tocumwal	Forested Wetlands / Grassy Woodlands	Murray Valley RP
The Riverine Grazier	1886	Tuppal	Semi-arid Woodlands (Shrubby)/Grassy Woodlands/Freshwater Wetlands	
Corowa Free Press	1887	Corowa District	Forested Wetlands	Murray Valley NP
Evening News	1888	Mudgee District	Dry Sclerophyll (Grassy & Shrubby)	Avisford NR
The Australian Star	1888	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
The Sydney Morning Herald	1888	Mandemar	Dry Sclerophyll (Shrubby & Grassy)/Grassy Woodlands	
Evening News	1888	Grenfell	Dry Sclerophyll (Shrubby)	Weddin Mountains NP/Conimbla NP
Goulburn Evening Penny	1888	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The Australian Star	1888	Queanbeyan	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Queanbeyan NR/Cuumbeun NR
Australian Star	1888	Braidwood	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Evening News	1888	Limekins	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Winburndale NR
Evening News	1888	Lithgow	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)/Heathlands	
Illawarra Mercury	1888	Bulli Mountain. Mount Keira and Mount Kembla	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra ESCA

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Evening News	1888	Black Ranges	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Grassy Woodlands/Rainforests/Forested Wetlands	Bournda NR
Evening News	1888	Braidwood	Wet Sclerophyll (Shrubby)/Dry Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Western Herald	1889	Within 8 miles of Gilgandra	Dry Sclerophyll (Shrubby & Grassy)/Forested Wetlands	
The Daily Telegraph	1889	Molong	Dry Sclerophyll (Shrubby)/Grassy Woodlands	
The Australian Star	1890	Pilliga	Dry (Grassy & Shrubby)/Semi-arid Woodlands (Shrubby)	Pilliga SCA/Pilliga NR
The Sydney Mail and New South Wales Advertiser	1890	Gilgandra	Dry Sclerophyll (Shrubby & Grassy)/Forested Wetlands	
National Advocate	1890	Grenfell	Dry Sclerophyll (Shrubby)	Weddin Mountains NP/Conimbla NP
The Dily Telegraph	1890	Ballina	Forested Wetlands	Ballina NR
Daily Telegraph	1890	Murrumbidgee	Forested Wetlands	Murrumbidgee Valley NP/Murrumbidgee Valley SCA
Newcastle Morning Herald and Miner’s Advocate	1890	Bogan	Semi-arid Woodlands (Shrubby)	Quanda NR
The Shoalhaven Telegraph	1890	Shoalhaven District	Wet Sclerophyll (Grassy & Shrubby)/Heathlands/Dry Sclerophyll (Shrubby)	Jerrawangala NP/Conjola NP
The Australian Star	1891	Yass	Dry Sclerophyll (Shrubby) / Grassy Woodlands	Mundoonen NR
Barrier Miner	1891	Condobolin	Semi-arid Woodlands (Shrubby)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Goulburn Evening Penny	1892	Bungonia	Dry Sclerophyll (Grassy & Shrubby)/Wet Sclerophyll (Grassy)/Heathlands	
The Daily Telegraph	1892	Mittagong District	Dry Sclerophyll (Grassy) / Grassy Woodlands	
The Australian Star	1892	Maryvale	Dry Sclerophyll (Grassy)/Grassy Woodlands	
Evening News	1892	Grenfell	Dry Sclerophyll (Shrubby)	Weddin Mountains NP/Conimbla NP
Sydney Mail and NSW Advertiser	1892	Rylstone	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Evening News	1892	Molong	Dry Sclerophyll (Shrubby)/Grassy Woodlands	
The Australian Star	1892	Bulli Mountains	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra ESCA
Wagga Wagga Express	1892	Murray Valley and Riverina Area	Forested Wetlands / Grassy Woodlands	Murray Valley NP
The Australian Star	1892	Tumberumba	Grassy Woodlands/Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	
Barrier Miner	1893	Wilcannia and White Cliffs opal fields	Arid Shrublands	Paroo-Darling NP
Barrier Miner	1893	Wilcannia	Arid Shrublands	Paroo-Darling NP
Goulburn Herald	1893	Narandera	Forested Wetlands / Grassy Woodlands / Semi-arid Woodlands (Shrubby)	Murrumbidgee Valley NR
Evening News	1893	Balranald	Forested Wetlands/Semi-arid Woodlands (Grassy)	Murrumbidgee Valley NP/Murrumbidgee Valley SCA
National Advocate	1893	Nymagee	Semi-arid Woodlands (Shrubby)	
The Kiama Independent, and Shoalhaven Advertiser	1894	Mount Victoria	Dry Sclerophyll (Grassy)	Blue Mountains NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Australian Star	1894	North West of Lawson	Dry Sclerophyll (Grassy)	Blue Mountains NP
The Kiama Independent, and Shoalhaven Advertiser	1894	Mittagong	Dry Sclerophyll (Grassy) / Grassy Woodlands	
The Armidale Chronicle	1894	Several districts around Armidale	Dry Sclerophyll (Shrubby & Grassy)	
National Advocate	1894	Mountains to the east of Bathurst	Dry Sclerophyll (Shrubby)	Winburndale NR
National Advocate	1894	Royal National Park	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Royal NP
Newcastle Morning Herald and Miner's Advocate	1894	Nelson Bay	Dry Sclerophyll (Shrubby)/Rainforests/Heathlands/Forested Wetlands	Tomaree NP
National Advocate	1894	Nowra	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	Triplarina NR/Worrigee NR
The Daily Telegraph	1894	Bulli Mountains	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
Evening News	1894	Berry District	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Rainforests/Heathlands	
The Daily Telegraph	1894	MacLean	Forested Wetlands/Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby)	Yaegl NR
Evening News	1895	Greta region	Dry Sclerophyll (Grassy)	
Evening News	1895	Hillgrove	Dry Sclerophyll (Grassy)	Oxley Wild Rivers NP
Evening News	1895	Gulgong	Dry Sclerophyll (Grassy) / Grassy Woodlands	
The Queanbeyan Observer	1895	Blue Mountains	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	Blue Mountains NP

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Goulburn Herald	1895	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
National Advocate	1895	Jerrys Plains	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Wollemi NP
Riverine Recorder	1895	Cooma and Pambala Districts	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	
The Australian Star	1895	Kurrajong Heights	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	Blue Mountains NP/Wollemi NP
Illawarra Mercury	1895	Mount Ousley and surrounds	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
Evening News	1895	Bega region/Black Range	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Grassy Woodlands/Rainforests/Forested Wetlands	Mimosa Rocks NP/Bournda NR
Illawarra Mercury	1895	Berry region	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Rainforests/Heathlands	
The Daily Telegraph	1895	Mudgee	Dry Sclerophyll (Shrubby & Grassy)	Avisford NR
Evening News	1895	Port Stephens to QLD border	Forested Wetlands/Dry Sclerophyll (Shrubby)/Saline Wetlands	Tomaree NP/Tilligerry NR
Evening News	1895	Gunnedah	Grassy Woodlands	
Dungog Chronicle: Durham and Gloucester Advertiser	1895	Bingleburra to Dungog	Wet Sclerophyll (Grassy & Shrubby)	
The Daily Telegraph	1895	Captains Flat	Wet Sclerophyll (Grassy & Shrubby)	Tallaganda NP
Evening News	1895	Wauchope to Beechwood and surrounds	Wet Sclerophyll (Grassy & Shrubby)	
The Daily Telegraph	1895	Moruya	Wet Sclerophyll (Grassy & Shrubby)/Dry Sclerophyll (Shrubby)/Grassy Woodlands	Eurobodalla NP
Goulburn Herald	1895	Wingham	Wet Sclerophyll (Grassy)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Queanbeyan Observer	1895	Braidwood	Wet Sclerophyll (Shrubby)/Dry Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Goulburn Herald	1896	Blue Mountains	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	Blue Mountains NP
National Advocate	1896	Mountains to the east of Bathurst	Dry Sclerophyll (Shrubby)	Winburndale NR
National Advocate	1896	Mountains to the east of Bathurst	Dry Sclerophyll (Shrubby)	Winburndale NR
The Australian Star	1896	Quarantine Station, North Head	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
Evening News	1896	Blue Mountains near Lithgow	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)/Heathlands	Blue Mountains NP
The Sydney Morning Herald	1896	Ballina	Forested Wetlands	Ballina NR
Evening News	1896	Coraki	Forested Wetlands	
The Daily Telegraph	1897	Branxton	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
The Daily Telegraph	1897	Capertee/Genowlan	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Gardens of Stone NP/Turon NP
Evening News	1897	Greta	Dry Sclerophyll (Grassy)	
Evening News	1897	Lawson	Dry Sclerophyll (Grassy)	Blue Mountains NP
Maitland Mercury	1897	Wattle Ponds	Dry Sclerophyll (Grassy)	
National Advocate	1897	Mount Rankin	Dry Sclerophyll (Shrubby & Grassy)/Freshwater Wetlands	
Evening News	1897	Nelson Bay	Dry Sclerophyll (Shrubby)/Rainforests/Heathlands/Forested Wetlands	Tomaree NP
Illawarra Mercury	1897	Mount Keira	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
The Sydney Morning Herald	1897	Narrandera	Semi-arid Woodlands (Shrubby)/Forested Wetlands	Murrumbidgee Valley NR
Glen Innes Examiner and General Advertiser	1897	Dungog	Wet Sclerophyll (Grassy & Shrubby)	
The Daily Telegraph	1897	Forster	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	
Macleay Argus	1897	Kempsey	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby & Grassy)	
Lithgow Mercury	1898	Blackheath/Medlow Bath	Dry Sclerophyll (Grassy)	Blue Mountains NP
Goulburn Herald	1898	Bombala	Dry Sclerophyll (Grassy) / Grassy Woodlands	Coolumbooka NR
Evening News	1898	Bowral	Dry Sclerophyll (Grassy) / Grassy Woodlands	
National Advocate	1898	Blue Mountains	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	Blue Mountains NP
Evening News	1898	Gara Falls, east of Armidale	Dry Sclerophyll (Shrubby)	Oxley Wild Rivers NP
National Advocate	1898	Mountains to the east of Bathurst	Dry Sclerophyll (Shrubby)	Winburndale NR
Evening News	1898	Quarantine Station, North Head	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
The Gundagai Independent and Pastoral, Agricultural and Mining Advocate	1899	Mountains between Murrumbidgee and Tumut Rivers	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
The Daily Telegraph	1899	Jenolan Caves	Dry Sclerophyll (Grassy)	Jenolan Karst Conservation Reserve

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Evening News	1899	Katoomba, Megalong Valley	Dry Sclerophyll (Grassy)	Blue Mountains NP
Evening News	1899	Moss Vale	Dry Sclerophyll (Grassy) / Grassy Woodlands	
Mudgee Guardian and North-Western Representative	1899	Warrumbungles	Dry Sclerophyll (Shrubby)	Warrumbungle NP
Evening News	1899	Quarantine Station, Collins Beach, North Head	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
Dubbo Dispatch and Wellington Independent	1899	Clarence	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	
Evening News	1899	Captains Flat	Wet Sclerophyll (Grassy & Shrubby)	Tallaganda NP
The Daily Telegraph	1900	Mount Cole	Dry Sclerophyll (Shrubby & Grassy)	Nangar NP
The Daily Telegraph	1900	Grenfell	Dry Sclerophyll (Shrubby)	Weddin Mountains NP/Conimbla NP
Australian Town and Country Journal	1900	Braidwood	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Molong Argus	1900	Molong	Dry Sclerophyll (Shrubby)/Grassy Woodlands	
Dubbo Dispatch and Wellington Independent	1900	Bombala	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Coolumbooka NR
The Daily Telegraph	1900	Mount Pleasant	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
Wingham Chronicle and Manning River Observer	1900	Tinonee	Forested Wetlands / Wet Sclerophyll (Grassy)	
Lithgow Mercury	1901	Between Hartley Vale and Bell	Dry Sclerophyll (Grassy)	Blue Mountains NP
The Sydney Morning Herald	1901	Springwood	Dry Sclerophyll (Grassy)	Blue Mountains NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Sydney Morning Herald	1901	Buchanan	Dry sclerophyll (Grassy) / Forested Wetlands / Wet Sclerophyll (Grassy)	
The Australian Star	1901	Collarenebri	Semi-arid Woodlands (Shrubby & Grassy)	
Lithgow Mercury	1902	Hassan’s Walls, Bowenfel	Dry Sclerophyll (Grassy)	
Mudgee Guardian and North-Western Guardian	1902	Ilford	Dry Sclerophyll (Grassy)	
Lithgow Mercury	1902	Jenolan Caves	Dry Sclerophyll (Grassy)	Jenolan Karst Conservation Reserve
Mudgee Guardian and North-Western Representative	1902	Hills between Mudgee and Grattai	Dry Sclerophyll (Shrubby & Grassy)	Avisford NR
The Armidale Express and New England General Advertiser	1902	Warialda	Dry Sclerophyll (Shrubby & Grassy)	Warialda SCA
The Sydney Morning Herald	1902	Araluen	Dry Sclerophyll (Shrubby & Grassy)/WSF Shrubby	Mongo NP
Evening News	1902	Lithgow	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)/Heathlands	
The Australian Star	1902	Murwillumbah	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	
The Daily Telegraph	1903	Eugowra	Dry Sclerophyll (Grassy)	Eugowra NR/Nangar NP
Evening News	1903	Nelson Bay	Dry Sclerophyll (Shrubby)/Rainforests/Heathlands/Forested Wetlands	Tomaree NP
Western Herald	1903	Gongolgon	Semi-arid Woodlands (Shrubby & Grassy)/Arid Shrublands (Chenopod)	
Albury Banner and Wodonga Express	1903	Dungog	Wet Sclerophyll (Grassy & Shrubby)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Warialda Standard and Northern District's Advertiser	1904	Boggabri	Dry Sclerophyll (Grassy & Shrubby)	
The Dubbo Liberal and Macquarie Advocate	1904	Geurie	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
The Australian Star	1904	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
Goulburn Evening Penny Post	1904	Hillgrove	Dry Sclerophyll (Grassy)	Oxley Wild Rivers NP
The Sydney Morning Herald	1904	Katoomba, Wentworth Falls and Medlow	Dry Sclerophyll (Grassy)	Blue Mountains NP
Australian Town and Country Journal	1904	Tamworth	Dry Sclerophyll (Grassy)	
Goulburn Evening Penny Post	1904	Bowral district	Dry Sclerophyll (Grassy) / Grassy Woodlands	
Monaco Mercury and Cooma and Bombala Advertiser	1904	Dungog, Gloucester, Lismore, and Inverell districts	Dry Sclerophyll (Grassy) / Grassy Woodlands / Rainforests / Wet Sclerophyll (Shrubby)	
The Sydney Morning Herald	1904	Wellington	Dry Sclerophyll (Grassy)/Grassy Woodlands	
Molong Express and Western District Advertiser	1904	Molong	Dry Sclerophyll (Shrubby)	
Mudgee Guardian and North-Western Representative	1904	Baradine	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Timallallie NP/Yarragin NP
Goulburn Evening Penny Post	1904	Bombala mountain range	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Coolumbooka NR
Goulburn Evening Penny Post	1904	Kangaroo Valley	Wet Sclerophyll (Grassy & Shrubby)/Rainforests/Dry Sclerophyll (Shrubby)	Kangaroo River NR

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Gosford Times and Wollombi Express	1905	Wollombi District	Dry Sclerophyll (Grassy)	Yengo NP
Bowral Free Press	1905	Moss Vale to Berrima	Dry Sclerophyll (Grassy) / Grassy Woodlands	
The Border Morning Mail and Riverina Times	1905	Sackville and Colo	Dry Sclerophyll (Grassy) / Grassy Woodlands	Wollemi NP
The Monaro Mercury, and Cooma and Bombala Advertiser	1905	Gunbar	Freshwater Wetlands/Semi-arid Woodlands (Shrubby & Grassy)/Arid Shrublands (Chenopod)	
Barrier Miner	1906	Wilcannia district	Arid Shrublands / Semi-arid Woodland	Paroo-Darling NP
Lithgow Mercury	1906	Blackheath	Dry Sclerophyll (Grassy)	Blue Mountains NP
Sydney Mail and NSW Advertiser	1906	Wheogo Mountain, near Grenfell	Dry Sclerophyll (Shrubby)	Conimbla NP
Argyle Liberal and District Recorder	1906	Wilcannia	Freshwater Wetlands/Semi-arid Woodlands (Shrubby)/Arid Shrublands (Chenopod)	Paroo-Darling NP
The Daily Telegraph	1907	Netallie Run, Wilcannia District	Arid Shrublands / Semi-arid Woodland	Paroo-Darling SCA
The Sydney Morning Herald	1907	Hills to the west of Mudgee	Dry Sclerophyll (Shrubby & Grassy)	Avisford NR
Lithgow Mercury	1907	Black Mountain	Grassy Woodlands	
The Hillston Spectator and Lachlan River Advertiser	1907	Ivanhoe	Semi-arid Woodlands (Shrubby)/Arid Shrublands (Chenopod)	Kajuligah NR/Wilandra NP
Leader	1908	Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
Mudgee Guardian and North-Western Representative	1909	Carwell	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
Western Champion	1909	Katoomba and Leura	Dry Sclerophyll (Grassy)	Blue Mountains NP

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
The Monaro Mercury, and Cooma and Bombala Advertiser	1909	Mountains between Bega and Cooma	Dry Sclerophyll (Grassy)/Wet Sclerophyll (Shrubby)	Wadbilliga NP/South East Forest NP
Blue Mountain Echo	1909	Woodford	Dry Sclerophyll (Shrubby)	Blue Mountains NP
The Inverell Times	1909	Brewarrina	Grasslands/Semi-arid Woodlands (Grassy)/Arid Shrublands (Acacia)	
Cobar Herald	1910	Tumbarumba	Dry Sclerophyll (Shrubby) / Grassy Woodlands / Wet Sclerophyll (Grassy)	
The Sydney Morning Herald	1910	Brewarrina	Grasslands/Semi-arid Woodlands (Grassy)/Arid Shrublands (Acacia)	
The independent	1910	Mathoura	Semi-arid Woodlands (Shrubby)/Grassy Woodlands/Freshwater Wetlands	Murray Valley RP
Sydney Morning Herald	1911	Blackheath	Dry Sclerophyll (Shrubby)	Blue Mountains NP
Barrier Miner	1911	Near Wentworth (30 miles x 20 miles, 100 miles in circumference)	Semi-arid Woodlands (Grassy & Shrubby)/Arid Shrublands (Chenopod)/Forested Wetlands	Mallee Cliffs NP
Western Grazier	1912	White Cliff	Arid Shrublands	Paroo-Darling NP/Mutawintji NP
The Maitland Daily Mercury	1912	Wentworth Falls	Dry Sclerophyll (Grassy)	Blue Mountains NP
The Armidale Chronicle	1912	Coramba and Dorrigo	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	Bindari NP/Dorrigo NP
The Bathurst Times	1912	Murwillumbah/Round Mountain	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	
The North Western Courier	1913	Pilliga	Dry (Grassy & Shrubby)/Semi-arid Woodlands (Shrubby)	Pilliga SCA/Pilliga NR
Newcastle Morning Herald and Miners' Advocate	1913	Near Cessnock	Dry Sclerophyll (Grassy & Shrubby)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Goulburn Evening Penny Post	1913	Weddin Mountain	Dry Sclerophyll (Grassy)	Weddin Mountains NP
The Maitland Daily Mercury	1913	Royal National Park	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Royal NP
Leader	1913	Cadia	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)/Grassy Woodlands	Mount Canobolas SCA
Leader	1914	Bathurst district	Dry Sclerophyll (Shrubby)	Winburndale NR
Lithgow Mercury	1914	Wallerawang	Dry Sclerophyll (Shrubby)	Marrangaroo NP
The Bathurst Times	1914	Rock Forest	Grassy Woodlands/Dry Sclerophyll (Grassy)/Freshwater Wetlands	
The Border Morning and Riverina Times	1914	Murray Valley	Semi-arid Woodlands (Shrubby)/Grassy Woodlands/Freshwater Wetlands	Murray Valley NP
Lithgow Mercury	1914	Black Springs	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Shrubby)	
Lithgow Mercury	1915	Hassan’s Walls	Dry Sclerophyll (Grassy)	
Daily Advertiser	1915	Wentworth Falls/Katoomba District	Dry Sclerophyll (Grassy)	Blue Mountains NP
The Daily Telegraph	1915	Tallong	Dry Sclerophyll (Shrubby & Grassy)	Moreton NP
Young Witness	1915	Grenfell	Dry Sclerophyll (Shrubby)	Weddin Mountains NP/Conimbla NP
Queanbeyan Age and Queanbeyan Observer	1915	Uriarra District	Dry Sclerophyll (Shrubby)	Brindabella NP
Molong Express and Western District Advertiser	1915	Gumble	Dry Sclerophyll (Shrubby)/Grassy Woodlands	South West Woodland NR
National Advocate	1915	Vittoria	DSF Shrubby	
The Armidale Chronicle	1915	Dorrigo District	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	Dorrigo NP
The Farmer and Settler	1915	Bellingen District	Wet Sclerophyll (Grassy)	

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
The Kyogle Examiner	1915	Tooloom	Wet Sclerophyll (Grassy)/Dry Sclerophyll (Grassy)/Rainforests	Yabbra NP
The Farmer and Settler	1916	Sharp's Creek Adelong to Wondalga and surrounds	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
The Gosford Times and Wyong District Advocate	1916	Bushland surrounding Brady's Gully Cemetery, Gosford	Dry Sclerophyll (Shrubby & Grassy)	
The Dubbo Liberal and Macquarie Advocate	1916	Bushland around Mogriguy	Dry Sclerophyll (Shrubby & Grassy)	Mogriguy NP/Goonoo NP
Leader	1916	Mullion Creek mountains	Dry Sclerophyll (Shrubby)	Mullion Range SCA
Goulburn Evening Penny	1916	Goulburn	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Evening News	1916	North Head	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
Daily Examiner	1917	Woodford Island	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Blue Mountains NP
Sydney Morning Herald	1918	Mutooroo, Scotia Blocks and Cuthero	Arid Shrublands	
The Scrutineer and Berrima District Press	1918	Mittagong District	Dry Sclerophyll (Grassy) / Grassy Woodlands	
Northern Star	1918	Rock Forest	Dry Sclerophyll (Shrubby & Grassy)/Grassy Woodlands/Freshwater Wetlands	
Goulburn Evening Penny	1918	Cookbundoon Range, near Goulburn	Dry Sclerophyll (Shrubby)	Cookbundoon NR

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Young Witness	1918	Yannawah	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
Northern Star	1918	Guerie	Grassy Woodlands/Dry Sclerophyll (Shrubby & Grassy)	
Daily Advertiser	1918	Menindee and Bourke districts	Semi-arid Woodlands	Kinchega NP
The Forbes Advocate	1918	Condobolin	Semi-Arid Woodlands (Shrubby)	
Western Herald	1918	West of Enngonia to Davis' Creek	Semi-Arid Woodlands (Shrubby)/Arid Shrublands (Acacia)	Ledknapper NR
Lithgow Mercury	1918	Duckmaloi	Wet Sclerophyll (Grassy)	
Maitland Daily Mercury	1919	Cessnock	Dry Sclerophyll (Grassy & Shrubby)	Werakata SCA
Northern Star	1919	Black Mountain	Grassy Woodlands	
Northern Star	1919	30 miles between Hargraves and Hill End	Grassy Woodlands/Dry Sclerophyll (Grassy & Shrubby)	
Moree Gwydir Examiner and General Advertiser	1919	Wattle Flat	Grassy Woodlands/Dry Sclerophyll (Shrubby)	
Mudgee Guardian and North-Western Representative	1919	Liverpool Range, Ardglen	Grassy Woodlands/Wet Sclerophyll (Grassy)	Murrurundi Pass NP
The Bathurst Times	1920	Mountains to the east of Bathurst	Dry Sclerophyll (Shrubby)	Winburndale NR
The Sydney Morning Herald	1920	Wisemans Ferry	Dry Sclerophyll (Shrubby)	Dharug NP
National Advocate	1920	Yetholme	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Eusdale NR/Winburndale NR
The Sun	1920	Mount Lambie	Dry Sclerophyll (Shrubby)/Grassy Woodlands/Wet Sclerophyll (Grassy)	

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
The Daily Telegraph	1921	Cobar to Wilcannia/Ivanhoe Districts	Arid Shrublands / Semi-arid Woodland	
The North Western Courier	1921	Pilliga Scrub/Pilliga East State Forest	Dry (Grassy & Shrubby)/Semi-Arid Woodlands (Shrubby)	Pilliga SCA/Pilliga NR
National Advocate	1921	Wellington	Dry Sclerophyll (Grassy)/Grassy Woodlands	
Albury Banner and Wodonga Express	1921	Hermidale and Miandetta districts	Semi-Arid Woodlands (Shrubby)	
The Riverine Grazier	1921	Ivanhoe	Semi-Arid Woodlands (Shrubby)/Arid Shrublands (Chenopod)	Kajuligah NR/Wilandra NP
The Corowa Free Press	1922	Holbrook District	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
The Sun	1922	Mittagong District	Dry Sclerophyll (Grassy) / Grassy Woodlands	
Mudgee Guardian and North-Western Representative	1922	Mark’s Gully and Sawpit Gully, south west of Mudgee	Dry Sclerophyll (Shrubby & Grassy)	Avisford NR
Mudgee Guardian and North-Western Representative	1922	Bomera Scrub	Dry Sclerophyll (Shrubby)	
Goulburn Evening Penny Post	1922	Royal National Park	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Royal NP
Illawarra Mercury	1922	Bulli Pass	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
Western Herald	1922	Between Bourke and Brewarrina	Grasslands/Semi-arid Woodlands (Grassy)/Arid Shrublands (Acacia)	
Mudgee Guardian and North-Western Representative	1922	Between Cudgegong and Rylstone	Heathlands/Dry Sclerophyll (Shrubby)	Wollemi NP
Northern Star	1923	Jamieson Valley	Dry Sclerophyll (Grassy & Shrubby)/Wet Sclerophyll (Shrubby)	Blue Mountains NP

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
The Farmer and Settler	1923	Wolumla	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Yurammie SCA/Bournda NR
Goulburn Evening Penny Post	1923	Yetholme Ranges	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Eusdale NR/Winburndale NR
Mudgee Guardian and North-Western Representative	1923	Hargraves	Grassy Woodlands/Dry Sclerophyll (Grassy & Shrubby)	
The Daily Express	1923	Woodenbong to Terrace Creek	Wet Sclerophyll (Grassy & Shrubby)/Dry Sclerophyll (Grassy)	
The Gundagai Independent and Pastoral, Agricultural and Mining Advocate	1924	Bethungra	Dry Sclerophyll (Shrubby & Grassy)/Semi-Arid Woodlands (Shrubby)	Ulandra NR
Goulburn Evening Settler	1925	Ashford	Grassy Woodlands	Kwiambal NP
Mudgee Guardian and North-Western Representative	1925	Merrygoen	Grassy Woodlands/Dry Sclerophyll (Grassy & Shrubby)	
Daily Advertiser	1926	Hills near Tumut	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	Wereboldera SCA/Kosciuzsko NP
The Braidwood Review and District Advocate	1926	Between Bungonia and Goulburn	Dry Sclerophyll (Grassy & Shrubby)/Wet Sclerophyll (Grassy)/Heathlands	
Wellington Times	1926	Walmer	Dry Sclerophyll (Grassy)/Grassy Woodlands	
Gilgandra Weekly	1926	Warrumbungles	Dry Sclerophyll (Shrubby)	Warrumbungle NP
The Forbes Advocate	1926	Weddin Mountains	Dry Sclerophyll (Shrubby)	Weddin Mountains NP
Riverina Recorder	1926	Balranald	Forested Wetlands/Semi-arid Woodlands (Grassy)	Murrumbidgee Valley NP/Murrumbidgee Valley SCA
Daily Express	1926	Meadow Flat	Grassy Woodlands	Eusdale NR

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Northern Star	1926	Kyogle District	Wet Sclerophyll (Grassy & Shrubby)	
The Manning River Times and Advocate for the Northern Districts of New South Wales	1926	Brother Mountain, Moorland	Wet Sclerophyll (Grassy & Shrubby)/Forested Wetlands	
The Dubbo Liberal and Macquarie Advocate	1927	Mogriguy	Dry Sclerophyll (Shrubby & Grassy)	Mogriguy NP/Goonoo NP
Glen Innes Examiner	1928	Mittagong	Dry Sclerophyll (Grassy) / Grassy Woodlands	
The Sydney Morning Herald	1928	Royal National Park	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Royal NP
Macleay Argus	1928	Corangula	Grassy Woodlands/Dry Sclerophyll (Grassy)/Wet Sclerophyll (Grassy)	
Barrier Miner	1928	Cal Lal	Semi-Arid Woodlands (Shrubby)/Arid Shrublands (Chenopod)	
The Uralla Times	1928	Thora District	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	Dorrigo NP
Daily Advertiser	1929	Holbrook	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
Northern Star	1929	Barrallier	Dry Sclerophyll (Grassy)	Blue Mountains NP
The Corowa Free Press	1929	Bigga	Dry Sclerophyll (Shrubby & Grassy)	Razorback NR/Keverstone NP
The Manning River Times and Advocate for the Northern Coast Districts of New South Wales	1929	Burraga	Dry Sclerophyll (Shrubby & Grassy)	
The Richmond River Express and Casino Kyogle Advertiser	1929	Blue Mountains, Bathurst and Jenolan Caves Districts	Dry Sclerophyll (Shrubby)	Blue Mountains NP
The Grenfell Record and Lachlan District Advertiser	1929	Grenfell/Weddin Mountain	Dry Sclerophyll (Shrubby)	Weddin Mountains NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Cootamundra Herald	1929	Goulburn District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The Armidale Express and New England General Advertiser	1929	Abercrombie Mountains, near Wombeyan Caves	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	Blue Mountains NP
The Manning River Times and Advocate for the Northern Coast Districts of New South Wales	1929	Katoomba and Lithgow Districts	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)/Heathlands	Blue Mountains NP
The Daily Telegraph	1929	Black Range	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)/Grassy Woodlands/Rainforests/Forested Wetlands	Bournda NR
The Cessnock Eagle and South Maitland Recorder	1930	Heddon Greta	Dry Sclerophyll (Grassy & Shrubby)	
Goulburn Evening Penny Post	1930	Tarlo Ranges (Goulburn District)	Dry Sclerophyll (Shrubby)	
The Sydney Morning Herald	1930	North Head	Dry Sclerophyll (Shrubby) / Heathlands	Sydney Harbour NP
Sydney Morning Herald	1931	40 miles east of Menindee	Arid Shrublands / Semi-arid Woodland	
Western Grazier	1931	43 miles from Wilcannia towards Cobar	Arid Shrublands / Semi-arid Woodland	Paroo-Darling NP
The Riverina Grazier	1931	Wilcannia between Tilpa and Bourke	Arid Shrublands / Semi-arid Woodland	Paroo-Darling NP
Mudgee Guardian and North-Western Representative	1931	Hills to the east of Mudgee	Dry sclerophyll (Shrubby & Grassy)	
The Uralla Times	1931	Cobar District (50-mile front)	Semi-Arid Woodlands (Shrubby & Grassy)/Arid Shrublands (Acacia)	
Barrier Miner	1931	Stirling Vale	Semi-Arid Woodlands (Shrubby)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Barrier Miner	1932	3 miles west of Ivanhoe	Arid Shrublands / Semi-arid Woodland	
Mudgee Guardian and North-Western Representative	1932	Eurunderee District	Dry Sclerophyll (Shrubby) / Grassy Woodlands	
The Katoomba Daily	1933	Katoomba	Dry Sclerophyll (Grassy)	Blue Mountains NP
The Propeller	1933	Royal National Park	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Royal NP
Gilgandra Weekly and Castlereagh	1933	Baradine	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Timallallie NP/Yarragin NP
National Advocate	1933	Yetholme District	Dry Sclerophyll (Shrubby)/Grassy Woodlands	Eusdale NR/Winburndale NR
Northern Star	1933	Tumbarumba	Dry Sclerophyll Shrubby / Grassy Woodlands / Wet Sclerophyll (Grassy)	
Mudgee Guardian and North-Western Representative	1933	Hargraves	Grassy Woodlands/Dry Sclerophyll (Grassy & Shrubby)	
The Braidwood Review and District Advocate	1933	Braidwood District	Wet Sclerophyll (Shrubby)/Dry Sclerophyll (Shrubby)	Mongo NP/Mongo SCA/Tallaganda SCA
Barrier Miner	1934	Hazelbrook	Dry Sclerophyll (Grassy)	Blue Mountains NP
The Cessnock Eagle and South Maitland Recorder	1934	Mount View, Cessnock District	Dry Sclerophyll (Grassy)	
The Maitland Mercury	1934	Vittoria	Dry Sclerophyll (Shrubby)	
Mudgee Guardian and North-Western Representative	1935	Mountains behind Denman	Dry Sclerophyll (Grassy & Shrubby)	
The Sydney Morning Herald	1935	Rydal District	Dry Sclerophyll (Shrubby)	Marrangaroo NP
The Daily Telegraph	1935	Long Mountain (south of Curlewis)	Grassy Woodlands	
The Blue Mountains Times	1936	Leura	Dry Sclerophyll (Grassy)	Blue Mountains NP

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Goulburn Evening Penny Post	1936	Mount Gibraltar, Bowral	Dry Sclerophyll (Grassy) / Grassy Woodlands	
The Braidwood Review and District Advocate	1936	Between Majors Creek and Araluen	Dry Sclerophyll (Shrubby & Grassy)/WSF Shrubby	Mongo NP
Mudgee Guardian and North-Western Representative	1936	Bomera	Dry Sclerophyll (Shrubby)	
The Daily Telegraph	1936	Catherine Hill Bay	Dry Sclerophyll (Shrubby)	Lake Macquarie SCA/Munmorah SCA/Wallarah NP
Macleay Argus	1936	Crescent Head	Forested Wetlands/Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Grassy)	Maria NP
The Gosford Times and Wyong District Advocate	1936	Palmdale	Wet Sclerophyll (Grassy & Shrubby)/Rainforests	
Western Herald	1937	Clifton Downs Station, 50 km east of Tibooburra	Arid Shrublands (Chenopod)/Semi-arid Woodlands (Grassy)	Pinderra Downs Aboriginal Area
Mudgee Guardian and North-Western Representative	1937	4 miles the Gulgong side of Ulan	Dry Sclerophyll (Shrubby)	
Western Herald	1937	Lissington Station, North west of Brewarrina, south of the QLD border	Grasslands/Semi-arid Woodlands (Grassy)/Arid Shrublands (Acacia)	Narran Lake NR
Mudgee Guardian and North-Western Representative	1938	Freemantle, Bathurst	Dry Sclerophyll (Shrubby)	Freemantle NR
Molong Express and Western District Advertiser	1938	Killongbutta State Forest	Dry Sclerophyll (Shrubby)	Freemantle NR
Mudgee Guardian and North-Western Representative	1939	Goonoo State Forest	Dry Sclerophyll (Shrubby & Grassy)	Goonoo SCA

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Mudgee Guardian and North-Western Representative	1939	Ranges beyond Mount Frome	Grassy Woodlands/Dry Sclerophyll (Shrubby)	
Western Grazier	1939	Barradale Station, 8 kms south east of Wilcannia	Semi-Arid Woodlands (Shrubby & Grassy)/Arid Shrublands (Chenopod)	Paroo-Darling SCA
Mudgee Guardian and North-Western Representative	1940	Capertee/Running Stream	Dry Sclerophyll (Grassy & Shrubby)	Gardens of Stone NP/Turon NP
Mudgee Guardian and North-Western Representative	1940	Hills to the south west of Mudgee	Dry Sclerophyll (Grassy & Shrubby)	Avisford NR
Cootamundra Herald	1940	Lacmalac	Dry Sclerophyll (Grassy & Shrubby)/Wet Sclerophyll (Grassy)	Kosciuszko NP
The Picton Post	1940	Wombeyan Caves District	Dry Sclerophyll (Grassy & Shrubby)/Wet Sclerophyll (Grassy)/Grassy Woodlands	Wombeyan Karst Conservation Reserve
Molong Express and Western District Advertiser	1940	Beyond Baldry towards Parkes and Alectown	Dry Sclerophyll (Shrubby)	Goobang NP
Molong Express and Western District Advertiser	1940	Norah Creek	Dry Sclerophyll (Shrubby)	South West Woodland NR
National Advocate	1940	Caloola	Dry Sclerophyll (Shrubby)/Freshwater Wetlands	
The Inverell Times	1940	Torrington	Dry Sclerophyll (Shrubby)/Heathlands/Grassy Woodlands	Torrington SCA
Illawarra Mercury	1940	Bulli	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
South Coast Times and Wollongong Argus	1940	West Wollongong	Dry Sclerophyll (Shrubby)/Wet Sclerophyll (Shrubby)	Illawarra Escarpment SCA
Daily Advertiser	1940	Mount Adrah	Grassy Woodlands/Dry Sclerophyll (Grassy)	Ellerslie NR
Border Morning Mail	1940	Woomargama	Grassy Woodlands/Dry Sclerophyll (Grassy)	Woomargama NP

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
Barrier Miner	1940	Hillston	Semi-arid Woodlands (Grassy)/Forested Wetlands	Lachlan Valley Regional Park
Mudgee Guardian and North-Western Representative	1941	Capertee/Running Stream	Dry Sclerophyll (Grassy & Shrubby)	Gardens of Stone NP/Turon NP
The Inverell Times	1941	Gum Flat	Dry Sclerophyll (Grassy & Shrubby)/Grassy Woodlands	
Daily Examiner	1941	Mylneford	Dry Sclerophyll (Grassy)/Grassy Woodlands	
The Propeller	1941	Royal National Park	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Royal NP
Molong Express and Western District Advertiser	1942	Wallerawang District and Newnes State Forest	Dry Sclerophyll Forest (Grassy & Shrubby)	Gardens of Stone NP/Wollemi NP
Singleton Argus	1942	Between East Greta and Heddon Greta	Dry Sclerophyll Forest (Grassy & Shrubby)/Forested Wetlands	
Daily Examiner	1942	Nymboida District	Dry Sclerophyll Forests (Grassy)	Chaelundi NP
Daily Examiner	1942	Upper Corindi	Forested Wetlands/Wet Sclerophyll (Grassy)/Dry Sclerophyll (Grassy)	
Barrier Miner	1942	Between Roto and Matakana	Semi-Arid Woodlands (Shrubby & Grassy)	Nombinnie NR/Lachlan Valley SCA
The North Western Courier	1943	Narrabri District, Edgeroi	Dry Sclerophyll Forests (Shrubby)	Bobbiwaa SCA
Northern Star	1943	Main Arm	Wet Sclerophyll Forests (Shrubby)/Rainforests	
Daily Examiner	1944	Scrub country 14 miles from Dubbo	Dry Sclerophyll Forests (Grassy & Shrubby)	Goonoo SCA
The Southern Mail	1944	Nattai Shire	Dry Sclerophyll Forests (Grassy & Shrubby)/Wet Sclerophyll Forests (Shrubby)	Burragorang SCA

Source	**Year**	**Location of fire**	**Predominant Vegetation Formation/sub-formation(s)**	**NSW NPWS Estate**
The Muswellbrook Chronicle	1944	Bells Mountain, McCully's Gap	Dry Sclerophyll Forests (Grassy)	
Yass Tribune-Courier	1944	Between Gundaroo and Collector	Dry Sclerophyll Forests (Shrubby)	McLeod's Creek NR
Lithgow Mercury	1945	The mountains south of Lithgow	Dry Sclerophyll Forests (Shrubby)/Wet Sclerophyll Forests (Grassy)	
Daily Advertiser	1946	Royal National Park	Dry Sclerophyll (Shrubby) / Wet Sclerophyll (Shrubby)	Royal NP
The Cessnock Eagle and South Maitland Recorder	1946	Bushland west of Cessnock	Dry Sclerophyll Forests (Grassy & Shrubby)	Werakata NP
Northern Star	1946	Huonbrook	Wet Sclerophyll Forests (Shrubby)/Rainforests	Mount Jerusalem NP/Goonengerry NP/Nightcap NP
Illawarra Mercury	1946	Scrub land near Coledale	Wet Sclerophyll Forests (Shrubby)/Rainforests	Dharawal NP
Barrier Miner	1947	Bend of the Darling River near Wilcannia	Arid Shrublands / Semi-arid Woodland	Paroo-Darling SCA
Lithgow Mercury	1947	Wallerawang	Dry Sclerophyll Forests (Shrubby)/Wet Sclerophyll Forests (Grassy)	Marrangaroo NP
Wellington Times	1948	40 miles south west of Broken Hill	Arid Shrublands	
Barrier Miner	1948	Wentworth Road, Broken Hill	Arid Shrublands	
Barrier Miner	1948	Woolcunda District	Arid Shrublands	
Barrier Miner	1948	Kudgee and Netley (SA) Districts	Arid Shrublands (Acacia & Chenopod)/Semi-Arid Woodlands (Shrubby)	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
National Advocate	1948	Between Cookamidgera and Mandagery	Dry Sclerophyll Forests (Shrubby)	Goobang NP
The Blue Mountains Advertiser	1948	Springwood	Dry Sclerophyll Forests (Shrubby)	Blue Mountains NP
Newcastle Morning Herald and Miner's Advocate	1949	Evans Head	Forested Wetlands/Heathlands/Dry Sclerophyll Forests (Shrubby)	Broadwater NP/Bundjalung NP
The Manning River Times and Advocate for the Northern Coast Districts of New South Wales	1949	Forster District	Forested Wetlands/Saline wetlands/Heathlands	
Barrier Miner	1950	Between Nundooka and Nappa Merrie	Arid Shrublands	
Goulburn Evening Post	1950	Bevendale District	Dry Sclerophyll Forests (Grassy & Shrubby)	
The Braidwood Review and District Advocate	1950	Marlowe District	Dry Sclerophyll Forests (Shrubby)	Nadgigomar NR
The Sydney Morning Herald	1950	Hills to the north of Lithgow	Dry Sclerophyll Forests (Shrubby)/Wet Sclerophyll Forests (Grassy)	
National Advocate	1950	Brewarrina District	Semi-arid Woodlands (Shrubby & Grassy)/Grasslands	
Barrier Daily Truth	1951	150 miles north of Broken Hill	Arid Shrublands	
Barrier Miner	1951	Bourke, Wanaaring, and Hungerford areas	Arid Shrublands / Semi-arid Woodland	Nocoleche NR/Toorale SCA
Western Herald	1951	Wanaaring District	Arid Shrublands / Semi-arid Woodland	Nocoleche NR
Warialda Standard and Northern Districts' Advertiser	1951	Warialda District	Dry Sclerophyll Forests (Grassy & Shrubby)	Warialda SCA
Mudgee Guardian and North-Western Representative	1951	Scrub country at Neilrex	Dry Sclerophyll Forests (Grassy & Shrubby)/Grassy Woodlands	

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Mudgee Guardian and North-Western Representative	1952	Scrub country towards Barney's Reef, Tallawang District	Dry Sclerophyll Forests (Shrubby)	
Illawarra Daily Mercury	1952	Wentworth Falls	Dry Sclerophyll Forests (Shrubby)	Blue Mountains NP
Daily Examiner	1952	Ku-ring-gai Chase	Dry Sclerophyll Forests (Shrubby)/Heathlands	Ku-ring-gai Chase NP
Daily Examiner	1952	Dobroyd Head, Balgowlah	Heathlands/Dry Sclerophyll Forests (Shrubby)	Sydney Harbour NP
Barrier Miner	1953	Blue Mountains, close to Glenbrook and Woodford	Dry Sclerophyll Forests (Shrubby)	Blue Mountains NP
The Cessnock Eagle and South Maitland Recorder	1954	Bush immediately to the south east of Cessnock	Dry sclerophyll Forests (Grassy & Shrubby)	Werakata NP
Mudgee Guardian and North-Western Representative	1954	2 miles from Clandulla	Dry sclerophyll Forests (Grassy & Shrubby)/Grassy Woodlands	
Goulburn Evening Post	1954	Governor's Hill	Dry Sclerophyll Forests (Shrubby)	
Windsor and Richmond Gazette	1955	Lower Portland	Dry sclerophyll Forests (Shrubby)/Wet Sclerophyll Forests (Shrubby)	Parr SCA
Western Herald	1956	Bourke District	Arid Shrublands / Semi-arid Woodland	Nocleche NR/Toorale SCA
Western Herald	1957	Bourke, Wanaaring, and Hungerford areas	Arid Shrublands / Semi-arid Woodland	Nocleche NR/Toorale SCA
Western Herald	1957	Wanaaring and Hungerford	Arid Shrublands / Semi-arid Woodland	Nocoleche NR

Source	Year	Location of fire	Predominant Vegetation Formation/sub-formation(s)	NSW NPWS Estate
Nepean Times	1957	Blue Mountains, Blaxland, Warrimoo and Glenbrook areas	Dry Sclerophyll Forests (Shrubby)	Blue Mountains NP
Western Herald	1958	Bourke, Wanaaring, and Hungerford areas	Arid Shrublands / Semi-arid Woodland	Nocleche NR/Toorale SCA
Western Herald	1960	Brewarrina District	Semi-arid Woodlands (Shrubby & Grassy)/Grasslands	
Western Herald	1969	Yantabulla	Arid Shrublands	

Appendix 3: Supplementary materials for Chapter Four

Additional details for each of the vegetation classes in NSW (Keith 2004; see Chapter 4.2.2) and the Interim Biogeographic Regionalisation for Australia (IBRA) bioregions (see Chapter 4.2.4) used in the analyses for Chapter Four. Additional graphs of distributions of time since fire through time, between regions of NSW, and among vegetation classes within each formation (see Chapters 4.4.1 and 4.4.3). Graphs of Kolmogorov-Smirnov tests of distributions of cumulative proportion of most recent fires in each year of known fire history from 2018 to 1926 between the NPWS_LMZ portion and the non-NPWS portion of each vegetation class in NSW (see Chapter 4.3.4).

Table A3. 1 Vegetation classes within NSW

For each vegetation class in NSW (Keith 2004) used in analysis: Class ID (E: East; W: West; X: Widespread; D: Dry; M: Moist; Alp: Alpine, ArAc/Ch: Arid Shrublands (Acacia sub-formation)/(Chenopod sub-formation); DSFG/S: Dry Sclerophyll Forests (Shrubby/Grassy sub-formation)/(Shrubby sub-formation); ForW: Forested Wetlands; FreW: Freshwater Wetlands; Gras: Grasslands; GrWd: Grassy Woodlands; Heat: Heathlands; Rain: Rainforests; SalW: Saline Wetlands; SAGr/Sh: Semi-arid Woodlands (Grassy sub-formation)/(Shrubby sub-formation); WSFG/S: Wet Sclerophyll Forests (Grassy sub-formation)/(Shrubby sub-formation); Class Name; area (ha) in NSW; percentage of each class within NPWS Estate LMZs; and minimum and maximum recommended fire intervals (based on Kenny *et al.* 2003). See Table 2.1 for formation names

ID	Class Name	Area (ha) in NSW	% of class in LMZ	Min. fire interval (years)	Max. fire interval (years)
E_D_Alp_1	Alpine Bogs and Fens	40 956	83	No burning	No burning
E_D_Apl_2*	Alpine Fjaeldmarks	156	14	No burning	No burning
E_D_Alp_3	Alpine Heaths	71 652	94	No burning	No burning
E_D_Alp_4	Alpine Herbfields	39 096	86	No burning	No burning
W_D_ArAc_5	Gibber Transition Shrublands	640 500	3	6	40
W_D_ArAc_6	North-west Plain Shrublands	997 104	2	6	40
W_D_ArAc_7	Sand Plain Mulga Shrublands	5 235 190	2	6	40
W_D_ArAc_8	Stony Desert Mulga Shrublands	1 969 252	7	6	40
W_D_ArCh_9	Aeolian Chenopod Shrublands	1 985 376	4	No burning	No burning
W_D_ArCh_10	Gibber Chenopod Shrublands	2 336 328	9	No burning	No burning
W_D_ArCh_11	Riverine Chenopod Shrublands	2 646 728	4	No burning	No burning
E_D_DSFG_12	Central Gorge DSF	270 872	60	5	50
E_D_DSFG_13	Clarence DSF	299 532	11	5	50
E_D_DSFG_14	Cumberland DSF	5 204	50	5	50
E_D_DSFG_15	Hunter-Macleay DSF	148 688	11	5	50
E_D_DSFG_16	New England DSF	161 060	22	5	50
E_D_DSFG_17	Northern Gorge DSF	410 692	43	5	50
E_D_DSFG_18	North-west Slopes Dry Sclerophyll Woodlands	817 536	11	5	50
X_D_DSFG_19	Pilliga Outwash DSF	314 112	29	5	50
E_D_DSFG_20	Southern Hinterland DSF	83 616	36	5	50

ID	Class Name	Area (ha) in NSW	% of class in LMZ	Min. fire interval (years)	Max. fire interval (years)
E_D_DSFG_21	Upper Riverina DSF	250 492	34	5	50
E_D_DSFS_22	Coastal Dune DSF	37 864	59	7	30
E_D_DSFS_23	North Coast DSF	135 396	21	7	30
E_D_DSFS_24	Northern Escarpment DSF	42 236	51	7	30
E_D_DSFS_25	Northern Tableland DSF	559 920	22	7	30
E_D_DSFS_26	South Coast Sands DSF	10 020	30	7	30
E_D_DSFS_27	South East DSF	459 324	42	7	30
E_D_DSFS_28	Southern Tableland DSF	917 456	32	7	30
E_D_DSFS_29	Southern Wattle DSF	6 380	49	7	30
E_D_DSFS_30	Sydney Coastal DSF	347 352	48	7	30
E_D_DSFS_31	Sydney Hinterland DSF	791 536	62	7	30
E_D_DSFS_32	Sydney Montane DSF	129 000	61	7	30
E_D_DSFS_33	Sydney Sand Flats DSF	20 000	40	7	30
E_D_DSFS_34	Western Slopes DSF	1 329 276	32	7	30
E_D_DSFS_35	Yetman DSF	82 700	24	7	30
E_M_ForW_36	Coastal Floodplain Forests	175 400	16	7	35
E_M_ForW_37	Coastal Swamp Forests	94 428	34	7	35
E_M_ForW_38	Eastern Riverine Forests	77 756	18	7	35
E_M_ForW_39	Floodplain Estuarine Transition Forests	20 408	16	7	35
W_M_ForW_40	Inland Riverine Forests	646 452	16	7	35
E_M_FreW_41	Coastal Freshwater Lagoon and Floodplain Meadows	27 020	23	6	35
E_M_FreW_42	Coastal Heath Swamps	25 504	58	6	35
W_M_FreW_43	Inland Floodplain Shrublands	1 148 536	3	6	35
W_M_FreW_44	Inland Floodplain Swamps	107 664	5	6	35
E_M_FreW_45	Montane Bogs and Fens	16 668	19	6	35
E_M_FreW_46*	Montane Lakes	4 168	8		
E_M_FreW_47	Temperate Swamp Forests	19 816	41	6	35
E_D_Gras_48	Maritime Grasslands	3 376	60	2	10
W_D_Gras_49	Riverine Plain Grasslands	114 188	0.4	2	10
W_D_Gras_50	Semi-arid Floodplain Grasslands	987 228	5	2	10

ID	Class Name	Area (ha) in NSW	% of class in LMZ	Min. fire interval (years)	Max. fire interval (years)
W_D_Gras_51**	Southern Riverina Grasslands	10 864	0	2	10
E_D_Gras_52	Temperate Montane Grasslands	41 248	4	2	10
X_D_Gras_53	Western Slopes Grasslands	179 892	3	2	10
E_D_GrWd_54	Coastal Valley Grassy Woodlands	118 264	10	5	40
X_D_GrWd_55	Floodplain Transition Woodlands	265 168	6	5	40
E_D_GrWd_56	New England Grassy Woodlands	288 972	6	5	40
E_D_GrWd_57	Southern Tablelands Grassy Woodlands	172 412	17	5	40
E_D_GrWd_58	Subalpine Woodlands	391 352	51	5	40
E_D_GrWd_59	Tableland Clay Grassy Woodlands	149 200	22	5	40
E_D_GrWd_60	Western Slopes Grassy Woodlands	511 580	4	5	40
E_D_Heat_61	Coastal Headland and Foredune Scrubs	6 956	53	7	30
E_D_Heat_62	Northern Montane Heaths	26 904	33	7	30
E_D_Heat_63	South Coast Heaths	2 184	91	7	30
E_D_Heat_64	Southern Montane Heaths	8 104	65	7	30
E_D_Heat_65	Sydney Coastal Heaths	22 436	56	7	30
E_D_Heat_66	Sydney Montane Heaths	89 812	74	7	30
E_D_Heat_67	Wallum Sand Heaths	17 656	53	7	30
E_M_Rain_68	Cool Temperate Rainforests	37 164	83	No burning	No burning
E_M_Rain_69	Dry Rainforests	76 696	50	No burning	No burning
E_M_Rain_70	Littoral Rainforests	3 112	54	No burning	No burning
E_M_Rain_71	Northern Warm Temperate Rainforests	194 480	57	No burning	No burning
E_M_Rain_72	Southern Warm Temperate Rainforests	12 124	46	No burning	No burning
E_M_Rain_73	Subtropical Rainforests	204 096	59	No burning	No burning
E_M_Rain_74	Western Vine Thickets	21 712	14	No burning	No burning
E_M_Rain_75*	Oceanic Cloud Forest	172	0	No burning	No burning
E_M_Rain_76*	Oceanic Rainforests	1 028	0	No burning	No burning
E_M_SalW_77	Mangrove Swamps	19 492	33	No burning	No burning
E_M_SalW_78	Saltmarshes	11 044	31	No burning	No burning
X_M_SalW_79	Seagrass Meadows	19 184	5	No burning	No burning
E_M_SalW_80*	Inland Saline Lakes	23 736	26	No burning	No burning

ID	Class Name	Area (ha) in NSW	% of class in LMZ	Min. fire interval (years)	Max. fire interval (years)
W_D_SASh_81*	Desert Woodlands	115 284	0	6	40
E_D_SASh_82	Dune Mallee Woodlands	1 222 032	7	6	40
W_D_SASh_83	Inland Rocky Hill Woodlands	472 124	7	6	40
X_D_SASh_84	North-west Alluvial Sand Woodlands	22 096	4	6	40
W_D_SASh_85	Riverine Sandhill Woodlands	114 216	5	6	40
W_D_SASh_86	Sand Plain Mallee Woodlands	1 279 608	15	6	40
W_D_SASh_87	Semi-arid Sand Plain Woodlands	3 838 332	4	6	40
W_D_SASh_88	Subtropical Semi-arid Woodlands	101 240	3	6	40
W_D_SASh_89	Western Peneplain Woodlands	4 436 480	5	6	40
X_D_SAGr_90	Brigalow Clay Plain Woodlands	29 708	3	6	40
W_D_SAGr_91	Inland Floodplain Woodlands	1 709 252	5	6	40
W_D_SAGr_92	North-west Floodplain Woodlands	2 075 740	6	6	40
W_D_SAGr_93	Riverine Plain Woodlands	218 944	3	6	40
W_D_SAGr_94	Wadi Woodlands	721 232	8	6	40
E_M_WSFG_95	Montane WSF	78 784	79	25	60
E_M_WSFG_96	Northern Hinterland WSF	828 296	19	25	60
E_M_WSFG_97	Northern Tableland WSF	394 892	37	25	60
E_M_WSFG_98	Southern Lowland WSF	181 092	33	25	60
E_M_WSFG_99	Southern Tableland WSF	287 804	51	25	60
E_M_WSFS_100	North Coast WSF	806 296	32	25	60
E_M_WSFS_101	Northern Escarpment WSF	131 512	58	25	60
E_M_WSFS_102	South Coast WSF	212 192	32	25	60
E_M_WSFS_103	Southern Escarpment WSF	207 248	52	25	60

* denotes classes not used in analyses; ** denotes classes with no fire history within NPWS LMZs and only used in NSW analyses

Table A3.2 Interim Biogeographic Regionalisation for Australia (IBRA) bioregions in NSW

For each IBRA bioregion in NSW: code used in paper; name; and area (Mha) in NSW

Code	Bioregion name	Area (Mha) in NSW
AUA	Australian Alps	0.5
BBS	Brigalow Belt South	5.6
BHC	Broken Hill Complex	3.8
CHC	Channel Country	2.3
COP	Cobar Peneplain	7.4
DRP	Darling Riverine Plains	9.4
MDD	Murray Darling Depression	7.9
MUL	Mulga Lands	6.6
NAN	Nandewar	2.1
NET	New England Tablelands	2.9
NNC	NSW North Coast	4
NSS	NSW South Western Slopes	8.1
RIV	Riverina	7
SEC	South East Corner	1.2
SEH	South East Highlands	4.9
SEQ	South east Queensland	1.7
SSD	Simpson Strzelecki Desert	1.1
SYB	Sydney Basin	3.6

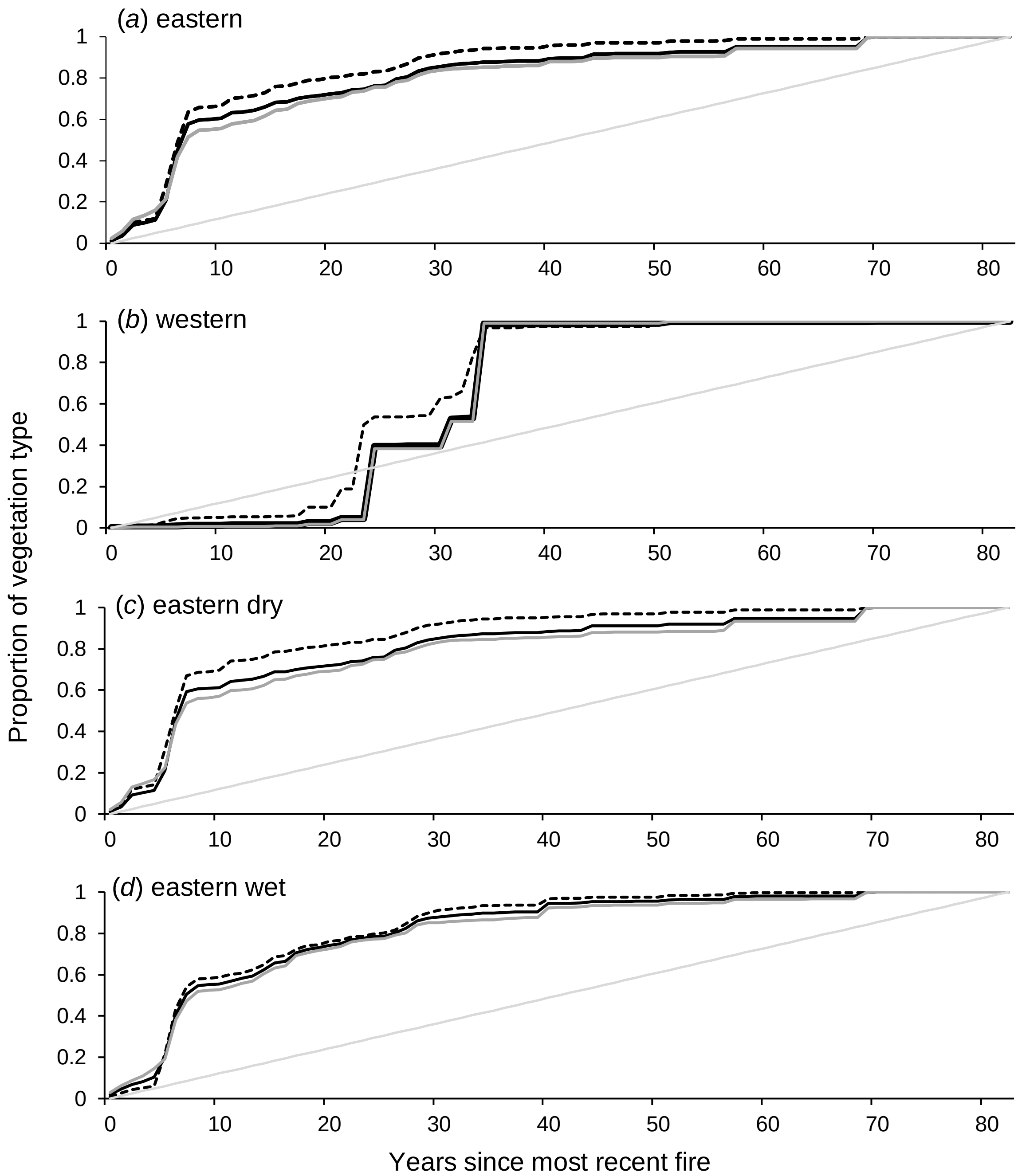


Figure A3.1 Cumulative proportion of most recent fires in each year of known fire history from 2008 to 1926 for NSW (black line), NPWS Estate (black dotted line), and non-NPWS Estate (grey line) for all eastern (a), all western (b), all eastern dry (c), and all eastern wet (d) formations. The diagonal lines represent an even distribution

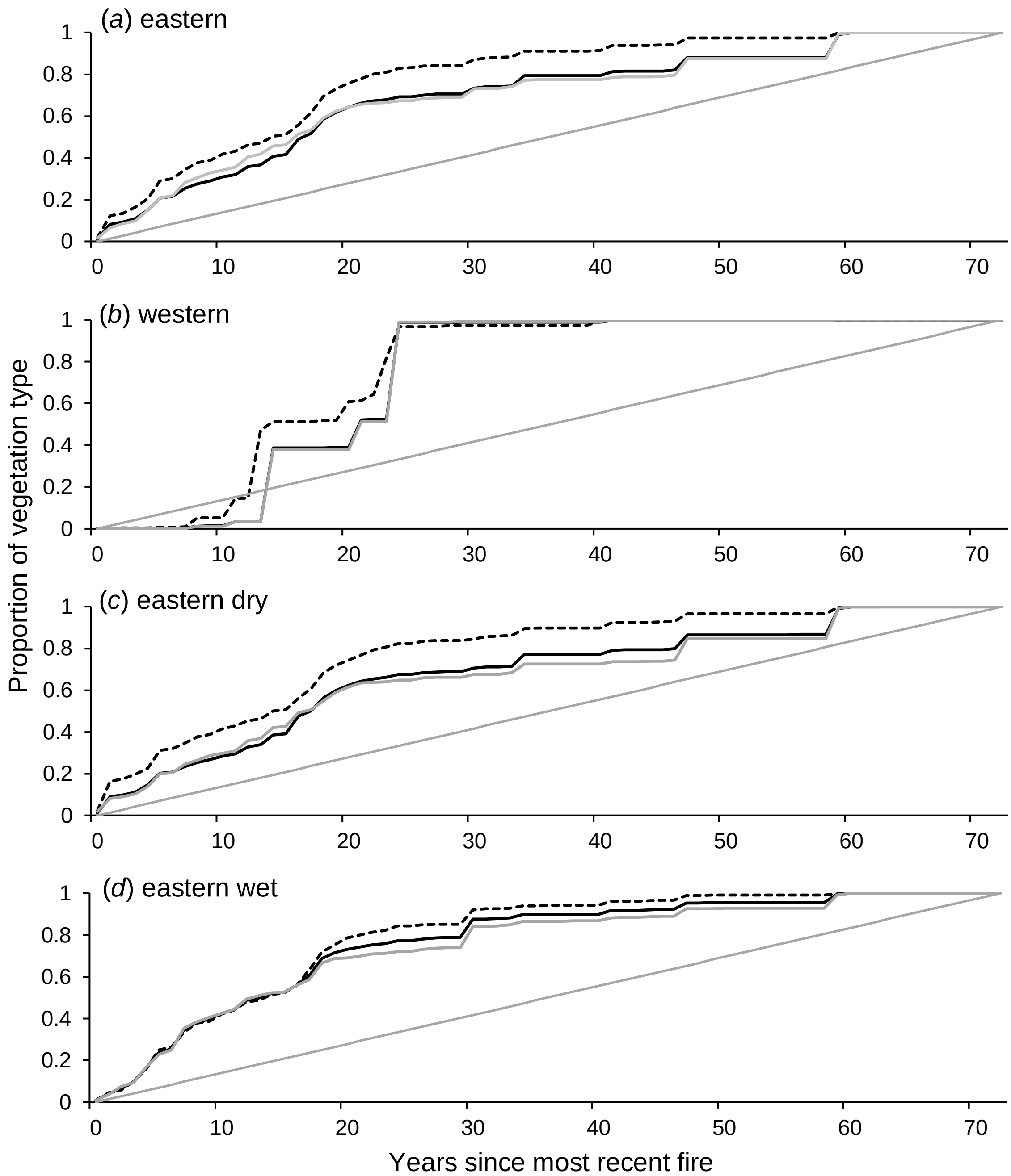


Figure A3.2 Cumulative proportion of most recent fires in each year of known fire history from 1998 to 1926 for NSW (black line), NPWS Estate (black dotted line), and non-NPWS Estate (grey line) for all eastern (a), all western (b), all eastern dry (c), and all eastern wet (d) formations. The diagonal lines represent an even distribution

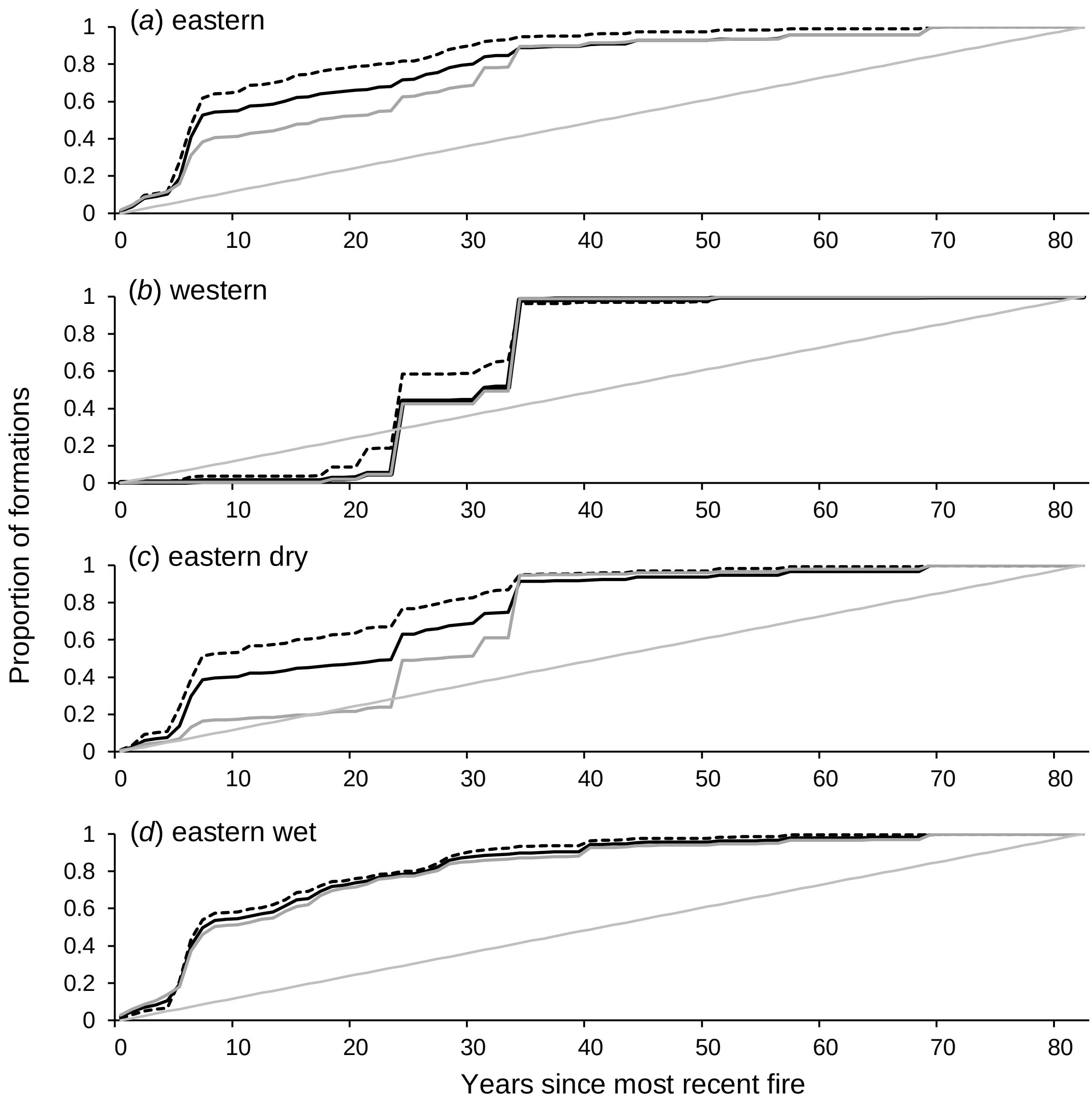


Figure A3.3 Cumulative proportion of most recent fires in each year of known fire history from 2008 to 1902 for NSW (black line), NPWS Estate (black dotted line), and non-NPWS Estate (grey line) for all eastern (*a*), all western (*b*), all dry (*c*), and all wet (*d*) classes. The diagonal lines represent an even distribution

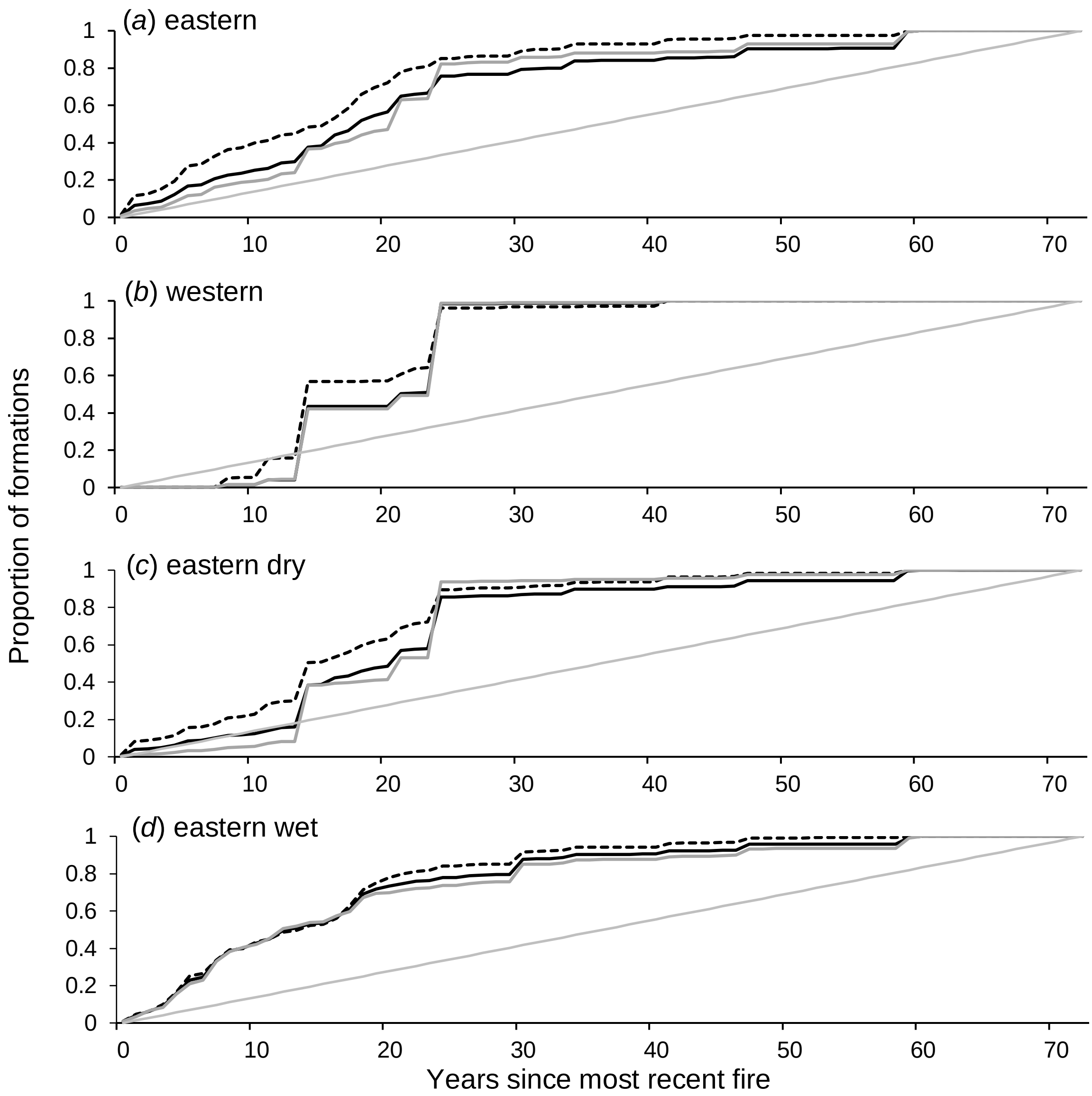


Figure A3.4 Cumulative proportion of most recent fires in each year of known fire history from 1998 to 1902 for NSW (black line), NPWS Estate (black dotted line), and non-NPWS Estate (grey line) for all eastern (a), all western (b), all dry (c), and all wet (d) classes. The diagonal lines represent an even distribution

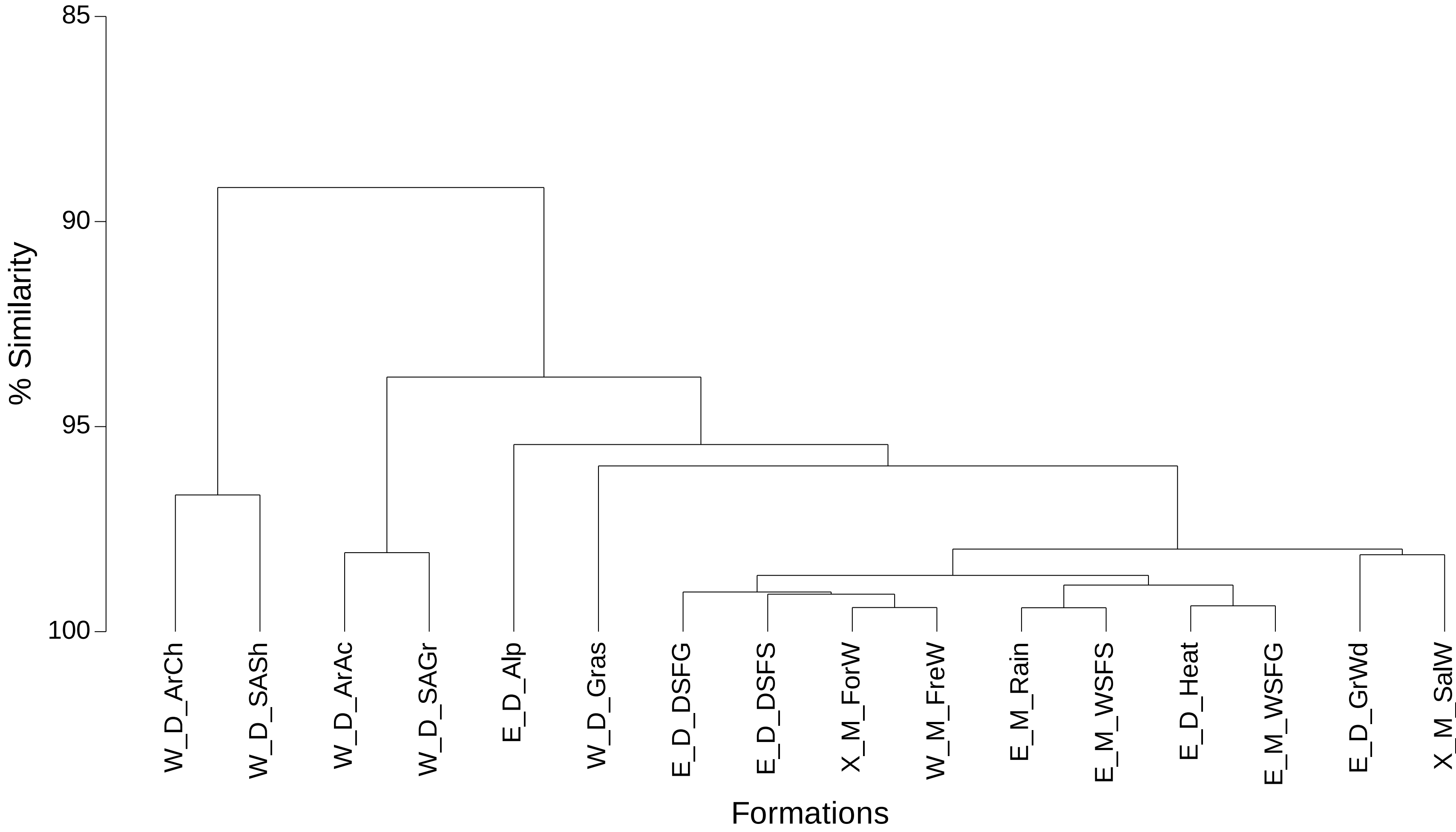
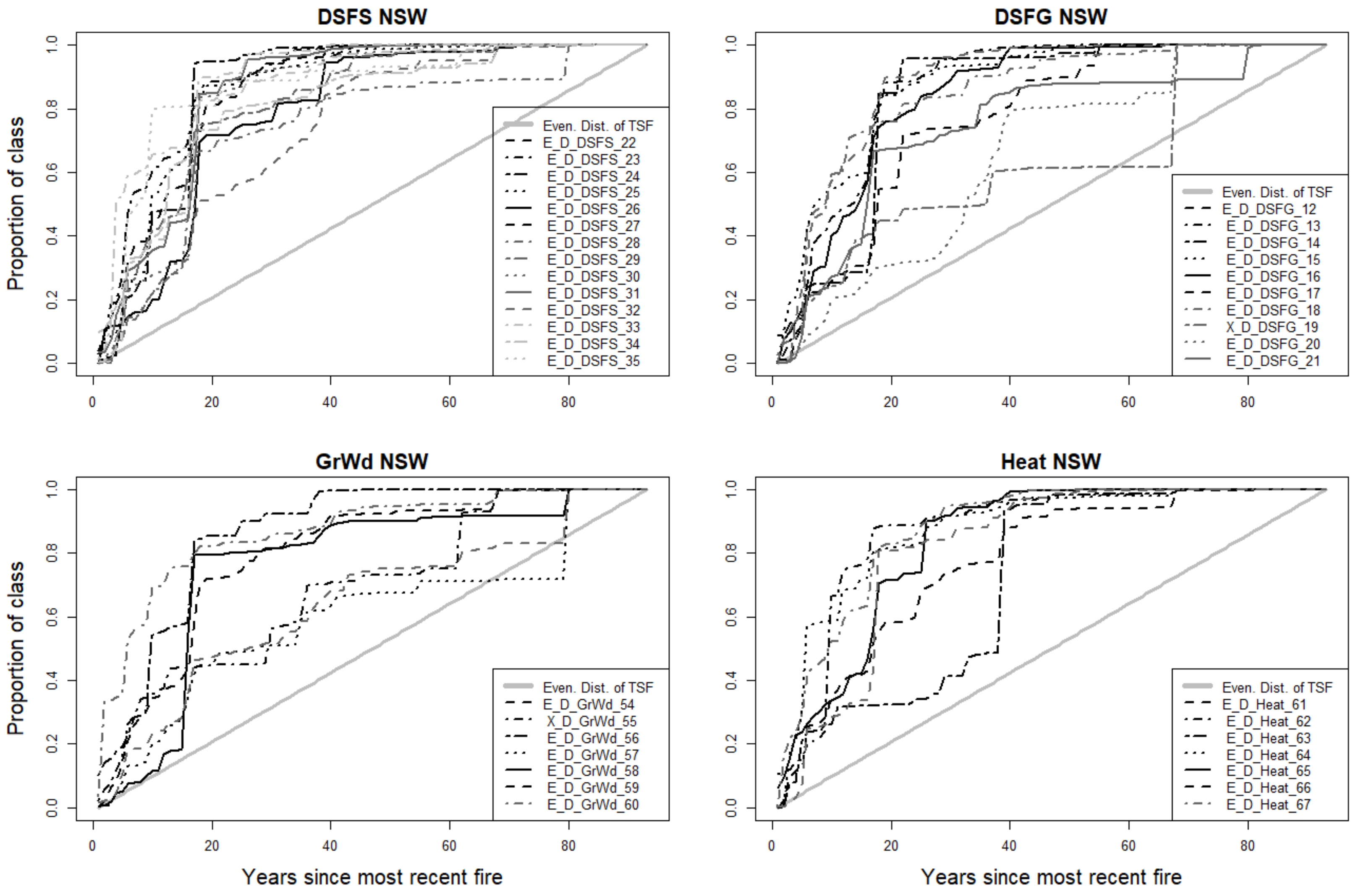
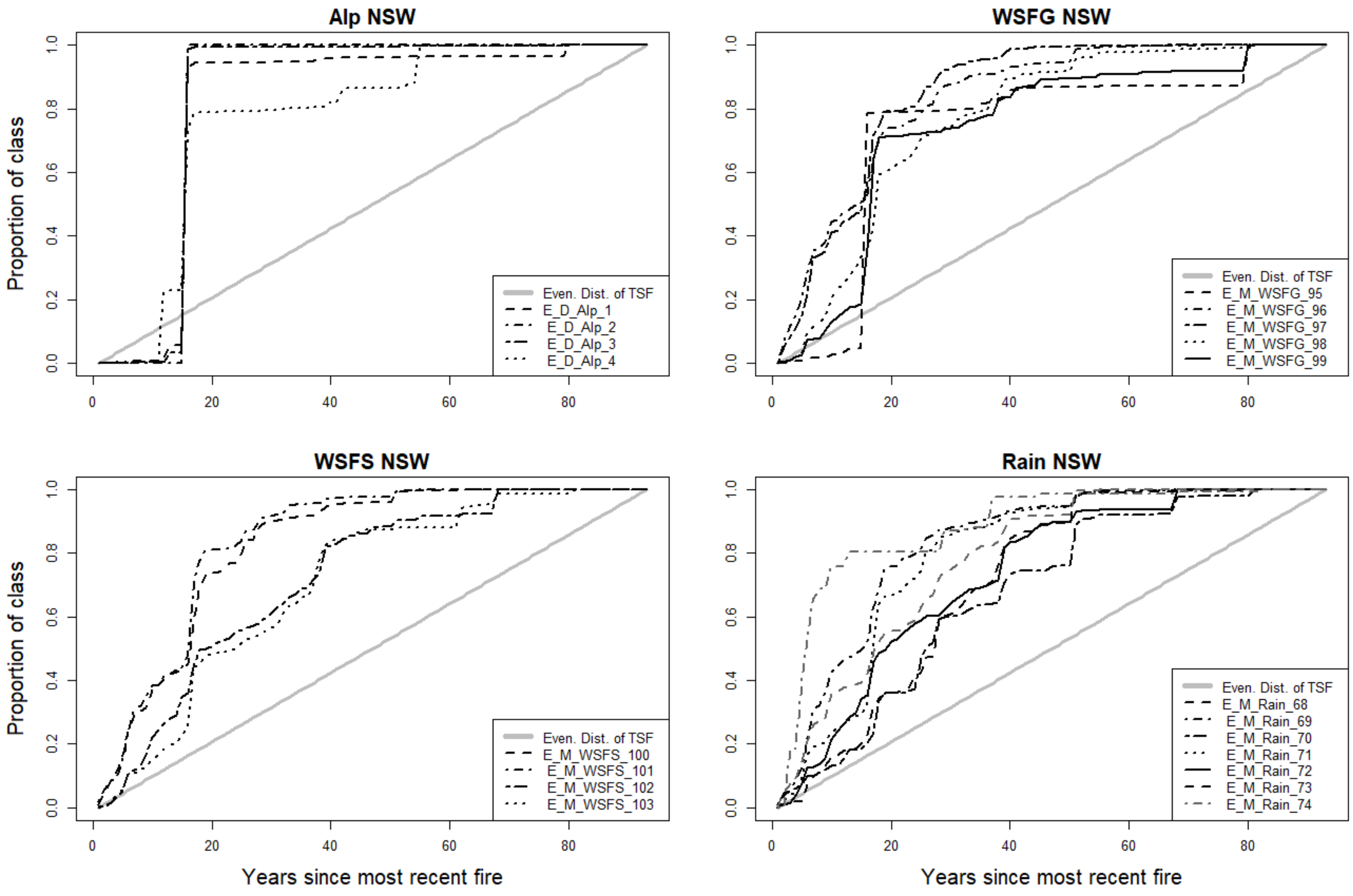
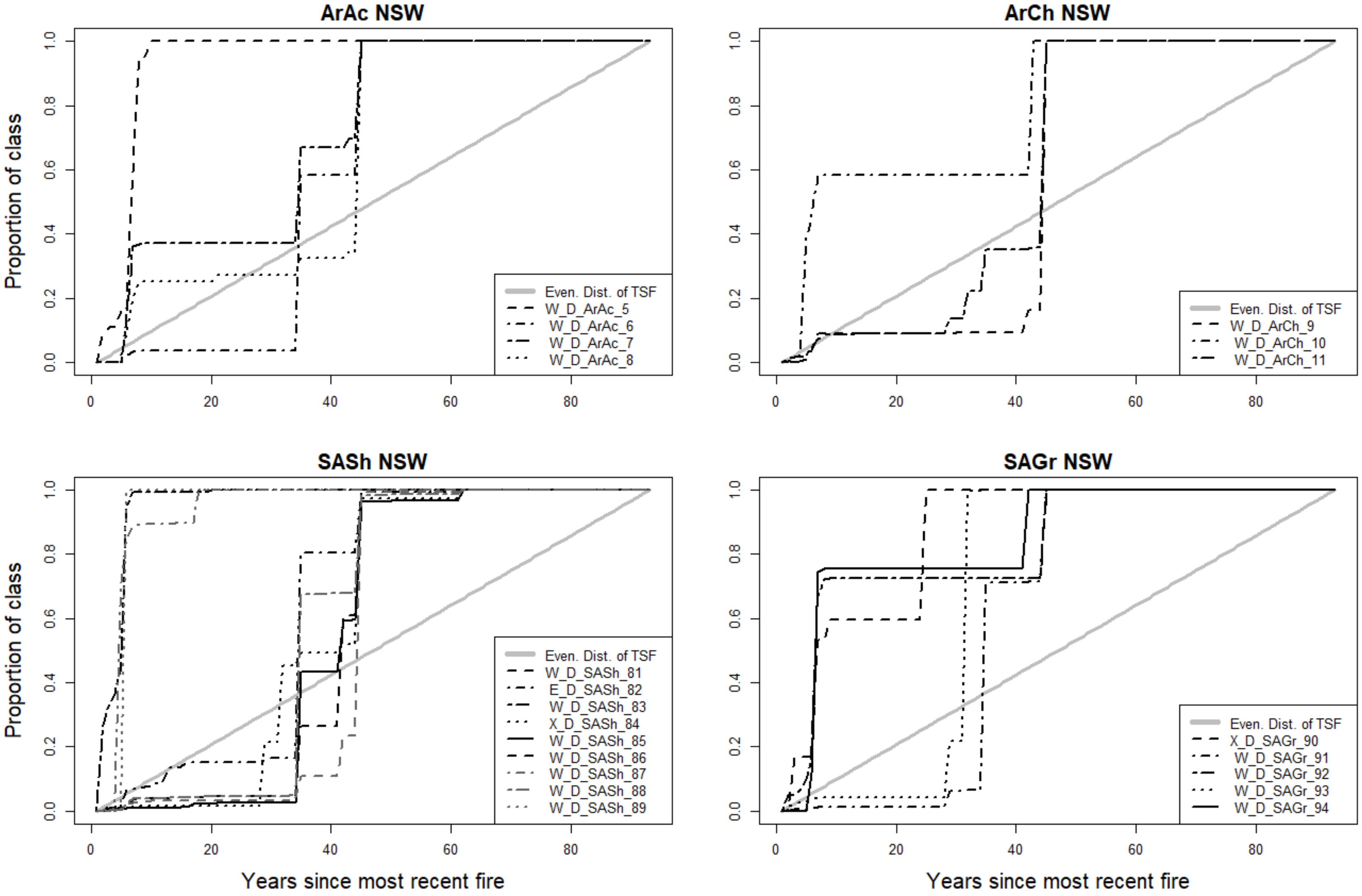
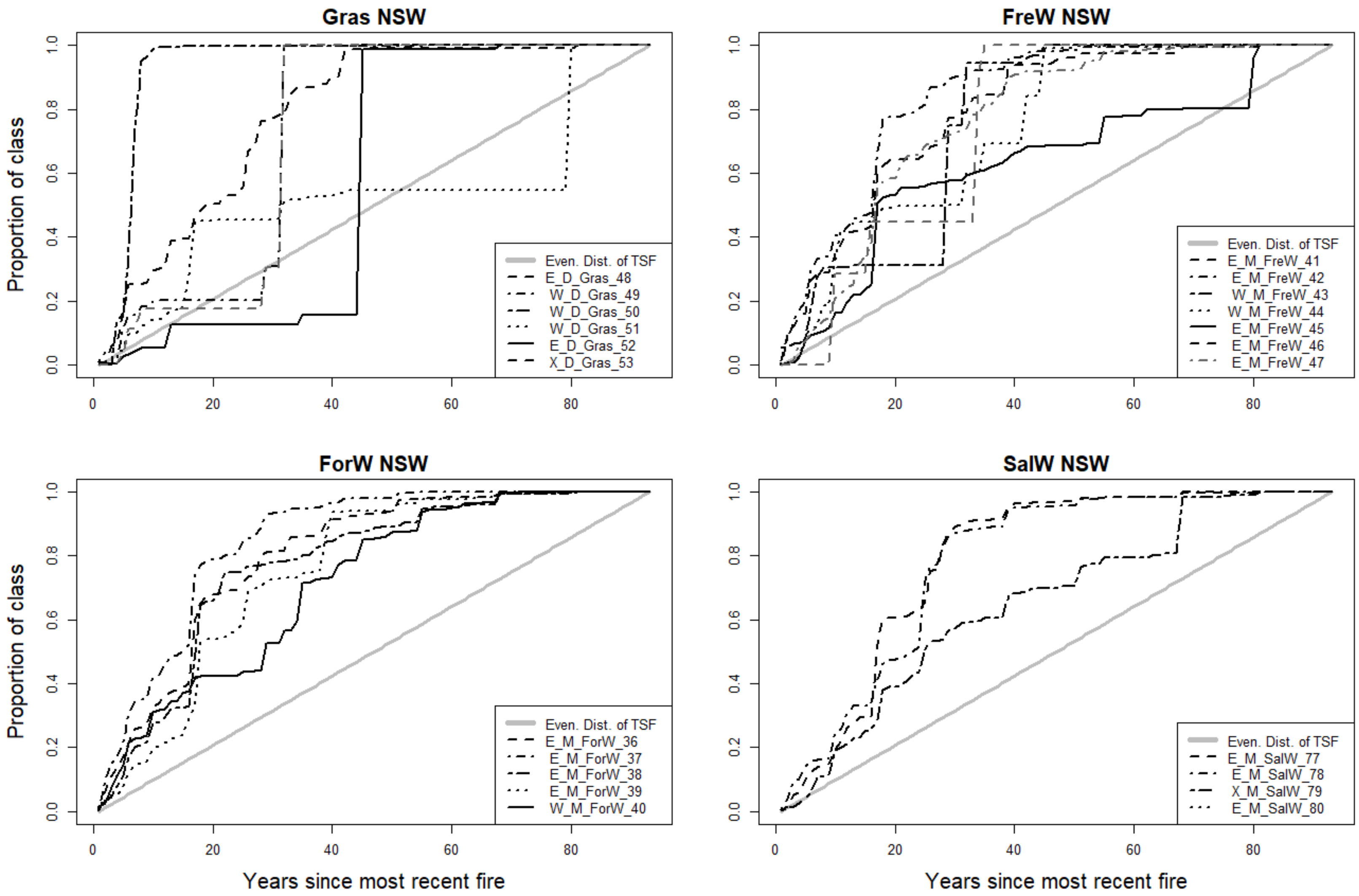


Figure A3.5 Bray-Curtis cluster analysis showing similarity between distributions of cumulative proportion of most recent fires in each year of known fire history from 2018 to 1926 for each vegetation formation within NPWS Estate. See Table 2.1 for formation names

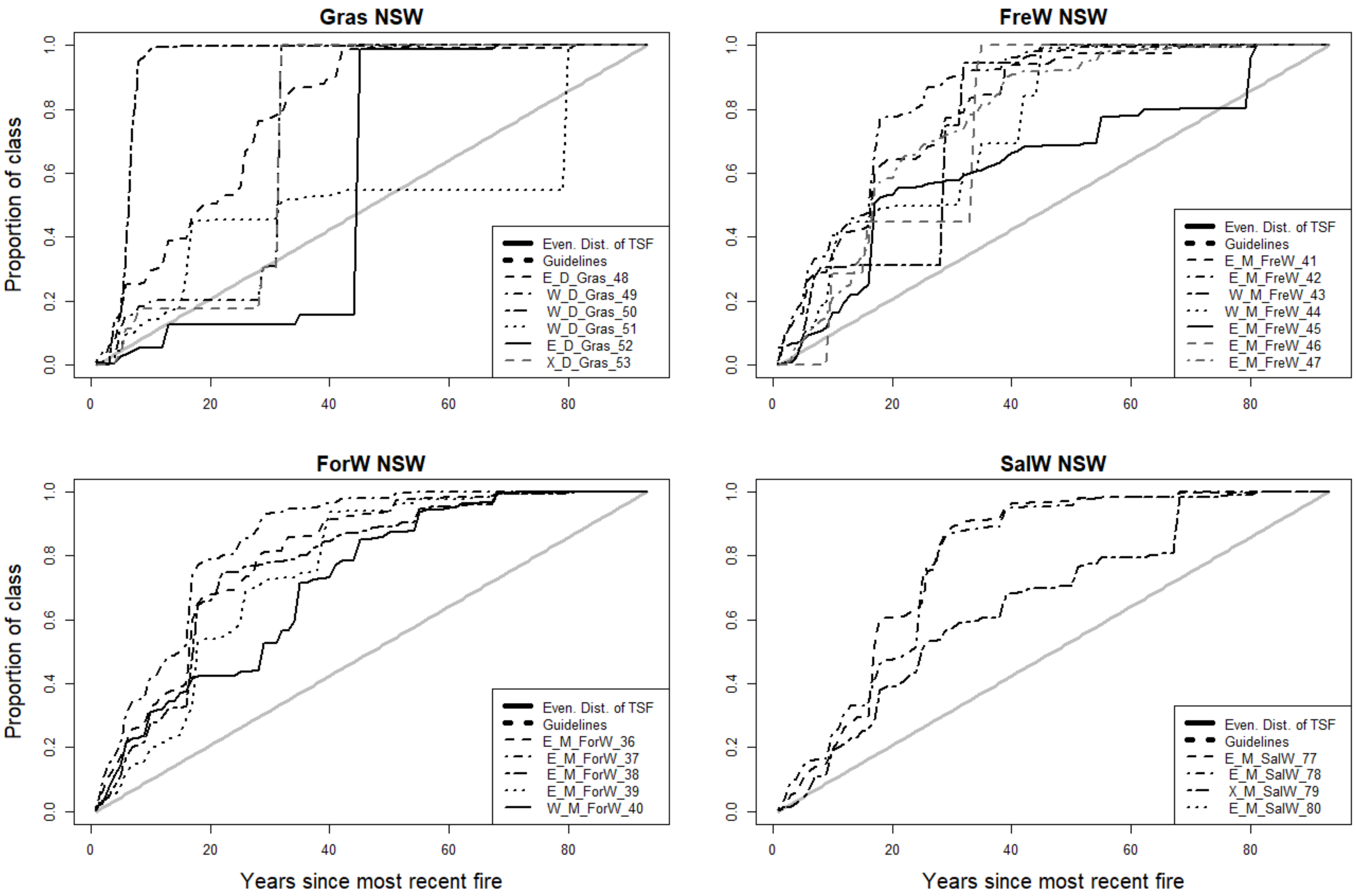

DSFS NSW
DSFG NSW
GrWd NSW
Heat NSW
Proportion of class
Years since most recent fire
Even. Dist. of TSF
E_D_DSFS_22
E_D_DSFS_23
E_D_DSFS_24
E_D_DSFS_25
E_D_DSFS_26
E_D_DSFS_27
E_D_DSFS_28
E_D_DSFS_29
E_D_DSFS_30
E_D_DSFS_31
E_D_DSFS_32
E_D_DSFS_33
E_D_DSFS_34
E_D_DSFS_35
E_D_DSFG_12
E_D_DSFG_13
E_D_DSFG_14
E_D_DSFG_15
E_D_DSFG_16
E_D_DSFG_17
E_D_DSFG_18
X_D_DSFG_19
E_D_DSFG_20
E_D_DSFG_21
E_D_GrWd_54
X_D_GrWd_55
E_D_GrWd_56
E_D_GrWd_57
E_D_GrWd_58
E_D_GrWd_59
E_D_GrWd_60
E_D_Heat_61
E_D_Heat_62
E_D_Heat_63
E_D_Heat_64
E_D_Heat_65
E_D_Heat_66
E_D_Heat_67


Alp NSW
Proportion of class
Even. Dist. of TSF
E_D_Alp_1
E_D_Alp_2
E_D_Alp_3
E_D_Alp_4
WSFG NSW
Even. Dist. of TSF
E_M_WSFG_95
E_M_WSFG_96
E_M_WSFG_97
E_M_WSFG_98
E_M_WSFG_99
WSFS NSW
Proportion of class
Even. Dist. of TSF
E_M_WSFS_100
E_M_WSFS_101
E_M_WSFS_102
E_M_WSFS_103
Years since most recent fire
Rain NSW
Even. Dist. of TSF
E_M_Rain_68
E_M_Rain_69
E_M_Rain_70
E_M_Rain_71
E_M_Rain_72
E_M_Rain_73
E_M_Rain_74
Years since most recent fire


ArAc NSW
Proportion of class
Even. Dist. of TSF
W_D_ArAc_5
W_D_ArAc_6
W_D_ArAc_7
W_D_ArAc_8
ArCh NSW
Even. Dist. of TSF
W_D_ArCh_9
W_D_ArCh_10
W_D_ArCh_11
SASh NSW
Proportion of class
Even. Dist. of TSF
W_D_SASh_81
E_D_SASh_82
W_D_SASh_83
X_D_SASh_84
W_D_SASh_85
W_D_SASh_86
W_D_SASh_87
W_D_SASh_88
W_D_SASh_89
Years since most recent fire
SAGr NSW
Even. Dist. of TSF
X_D_SAGr_90
W_D_SAGr_91
W_D_SAGr_92
W_D_SAGr_93
W_D_SAGr_94
Years since most recent fire



Gras NSW
Even. Dist. of TSF
E_D_Gras_48
W_D_Gras_49
W_D_Gras_50
W_D_Gras_51
E_D_Gras_52
X_D_Gras_53
FreW NSW
Even. Dist. of TSF
E_M_FreW_41
E_M_FreW_42
W_M_FreW_43
W_M_FreW_44
E_M_FreW_45
E_M_FreW_46
E_M_FreW_47
ForW NSW
Even. Dist. of TSF
E_M_ForW_36
E_M_ForW_37
E_M_ForW_38
E_M_ForW_39
W_M_ForW_40
SalW NSW
Even. Dist. of TSF
E_M_SalW_77
E_M_SalW_78
X_M_SalW_79
E_M_SalW_80
Proportion of class
Years since most recent fire


Gras NSW
FreW NSW
ForW NSW
SalW NSW
Proportion of class
Years since most recent fire
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
Even. Dist. of TSF
Guidelines
E_D_Gras_48
W_D_Gras_49
W_D_Gras_50
W_D_Gras_51
E_D_Gras_52
X_D_Gras_53
E_M_FreW_41
E_M_FreW_42
W_M_FreW_43
W_M_FreW_44
E_M_FreW_45
E_M_FreW_46
E_M_FreW_47
E_M_ForW_36
E_M_ForW_37
E_M_ForW_38
E_M_ForW_39
W_M_ForW_40
E_M_SalW_77
E_M_SalW_78
X_M_SalW_79
E_M_SalW_80

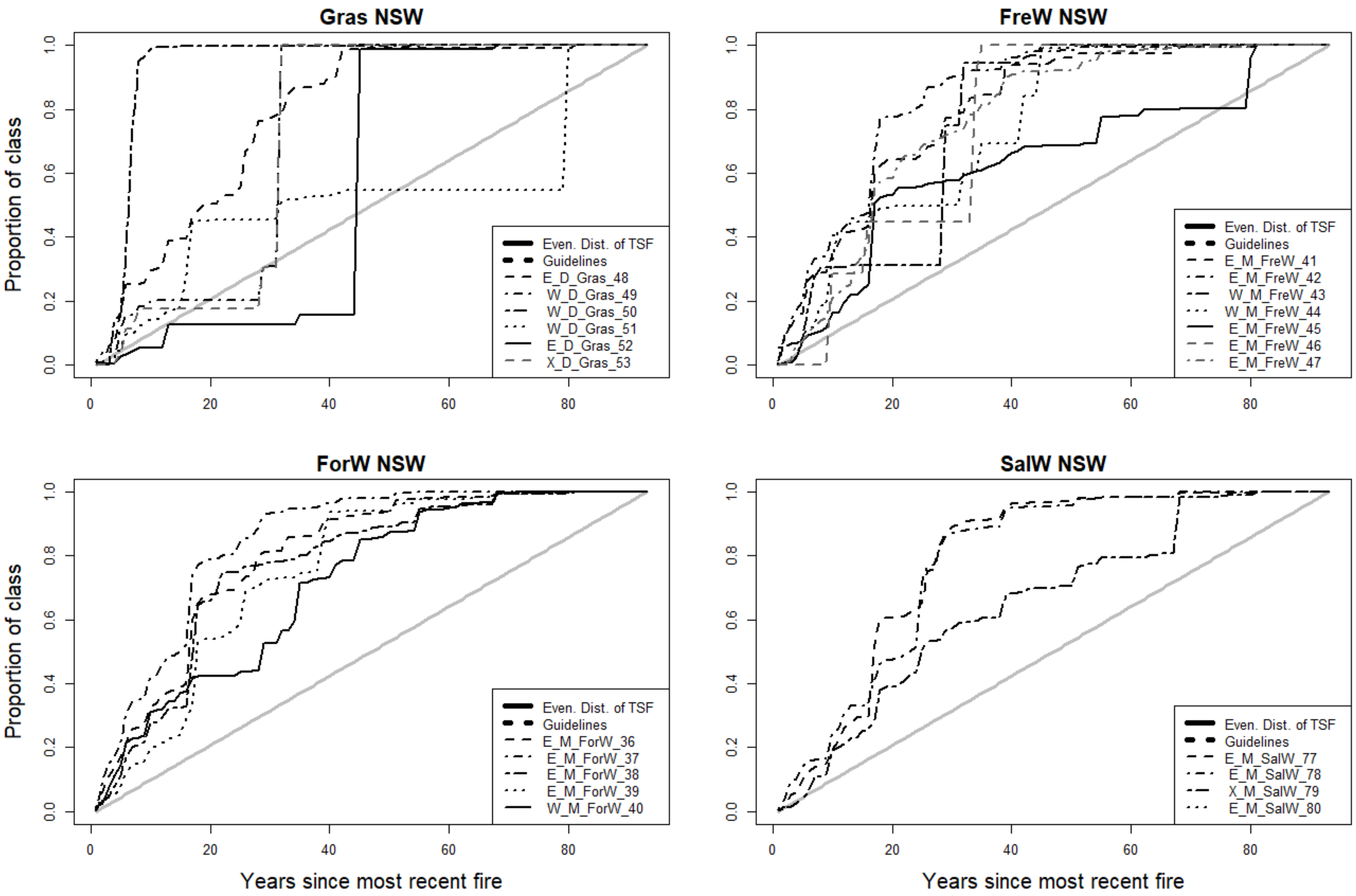
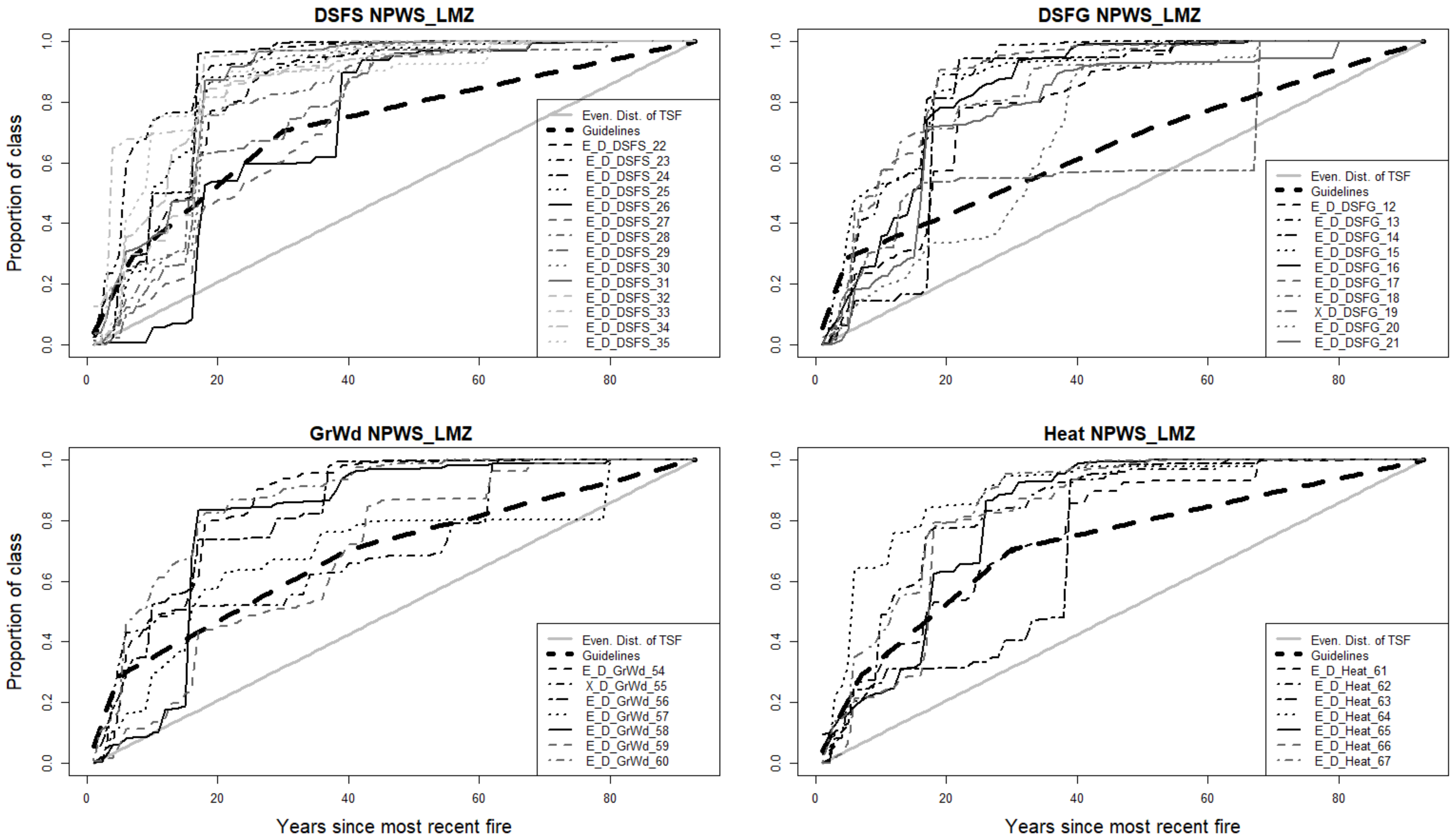
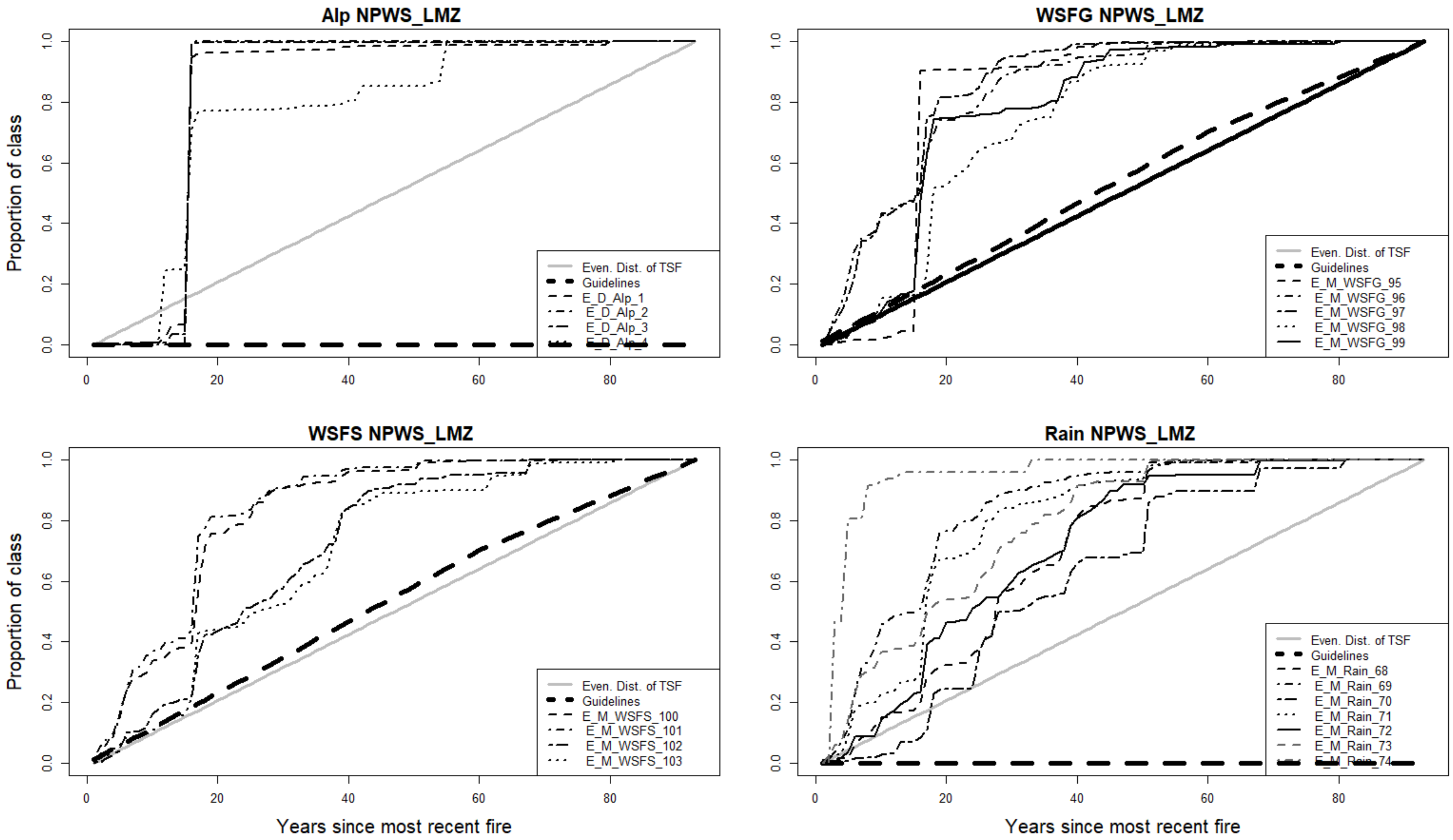
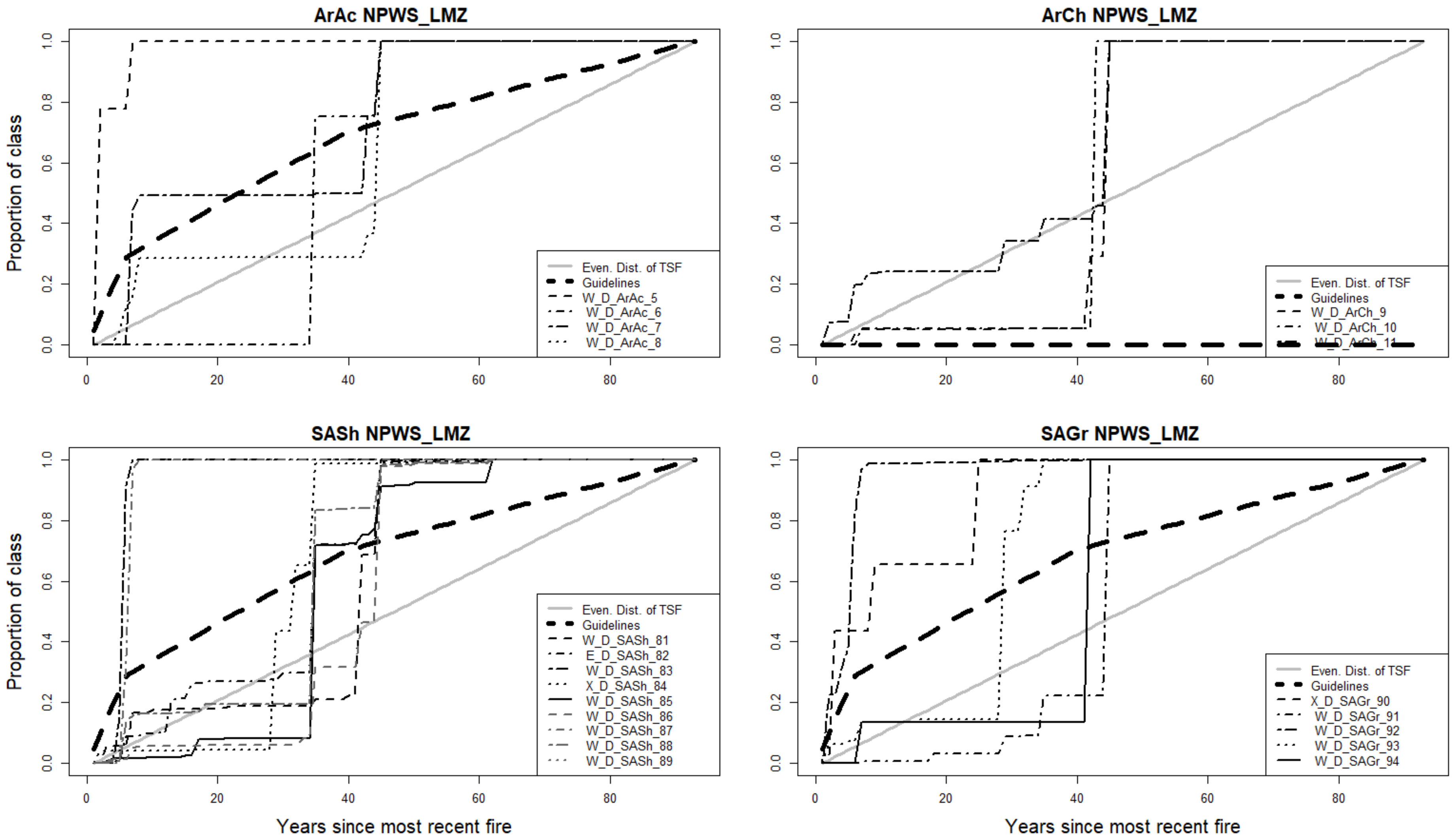


Figure A3.6 Cumulative proportion of most recent fires in each year of known fire history from 1998 to 1902 for each vegetation class within each formation in NSW. The thick black line represents an even distribution


DSFS NPWS_LMZ
Proportion of class
Even. Dist. of TSF
Guidelines
E_D_DSFS_22
E_D_DSFS_23
E_D_DSFS_24
E_D_DSFS_25
E_D_DSFS_26
E_D_DSFS_27
E_D_DSFS_28
E_D_DSFS_29
E_D_DSFS_30
E_D_DSFS_31
E_D_DSFS_32
E_D_DSFS_33
E_D_DSFS_34
E_D_DSFS_35
DSFG NPWS_LMZ
Even. Dist. of TSF
Guidelines
E_D_DSFG_12
E_D_DSFG_13
E_D_DSFG_14
E_D_DSFG_15
E_D_DSFG_16
E_D_DSFG_17
E_D_DSFG_18
X_D_DSFG_19
E_D_DSFG_20
E_D_DSFG_21
GrWd NPWS_LMZ
Proportion of class
Even. Dist. of TSF
Guidelines
E_D_GrWd_54
X_D_GrWd_55
E_D_GrWd_56
E_D_GrWd_57
E_D_GrWd_58
E_D_GrWd_59
E_D_GrWd_60
Years since most recent fire
Heat NPWS_LMZ
Even. Dist. of TSF
Guidelines
E_D_Heat_61
E_D_Heat_62
E_D_Heat_63
E_D_Heat_64
E_D_Heat_65
E_D_Heat_66
E_D_Heat_67
Years since most recent fire


Alp NPWS_LMZ
WSFG NPWS_LMZ
WSFS NPWS_LMZ
Rain NPWS_LMZ
Proportion of class
Years since most recent fire
Even. Dist. of TSF
Guidelines
E_D_Alp_1
E_D_Alp_2
E_D_Alp_3
E_D_Alp_4
E_M_WSFG_95
E_M_WSFG_96
E_M_WSFG_97
E_M_WSFG_98
E_M_WSFG_99
E_M_WSFS_100
E_M_WSFS_101
E_M_WSFS_102
E_M_WSFS_103
E_M_Rain_68
E_M_Rain_69
E_M_Rain_70
E_M_Rain_71
E_M_Rain_72
E_M_Rain_73
E_M_Rain_74


ArAc NPWS_LMZ
ArCh NPWS_LMZ
SASh NPWS_LMZ
SAGr NPWS_LMZ
Proportion of class
Years since most recent fire
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
Even. Dist. of TSF
Guidelines
W_D_ArAc_5
W_D_ArAc_6
W_D_ArAc_7
W_D_ArAc_8
W_D_ArCh_9
W_D_ArCh_10
W_D_ArCh_11
W_D_SASh_81
E_D_SASh_82
W_D_SASh_83
X_D_SASh_84
W_D_SASh_85
W_D_SASh_86
W_D_SASh_87
W_D_SASh_88
W_D_SASh_89
X_D_SAGr_90
W_D_SAGr_91
W_D_SAGr_92
W_D_SAGr_93
W_D_SAGr_94

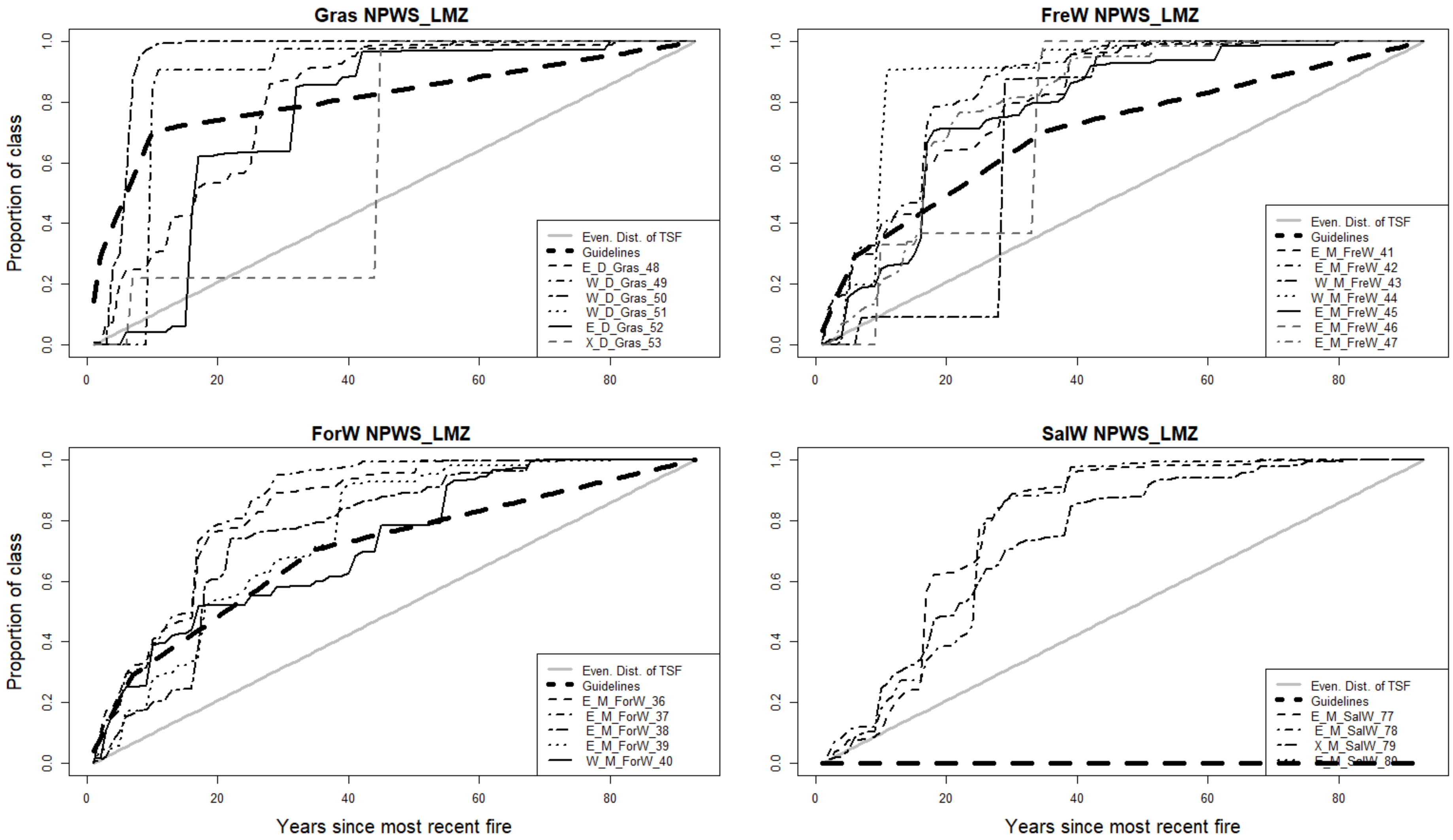
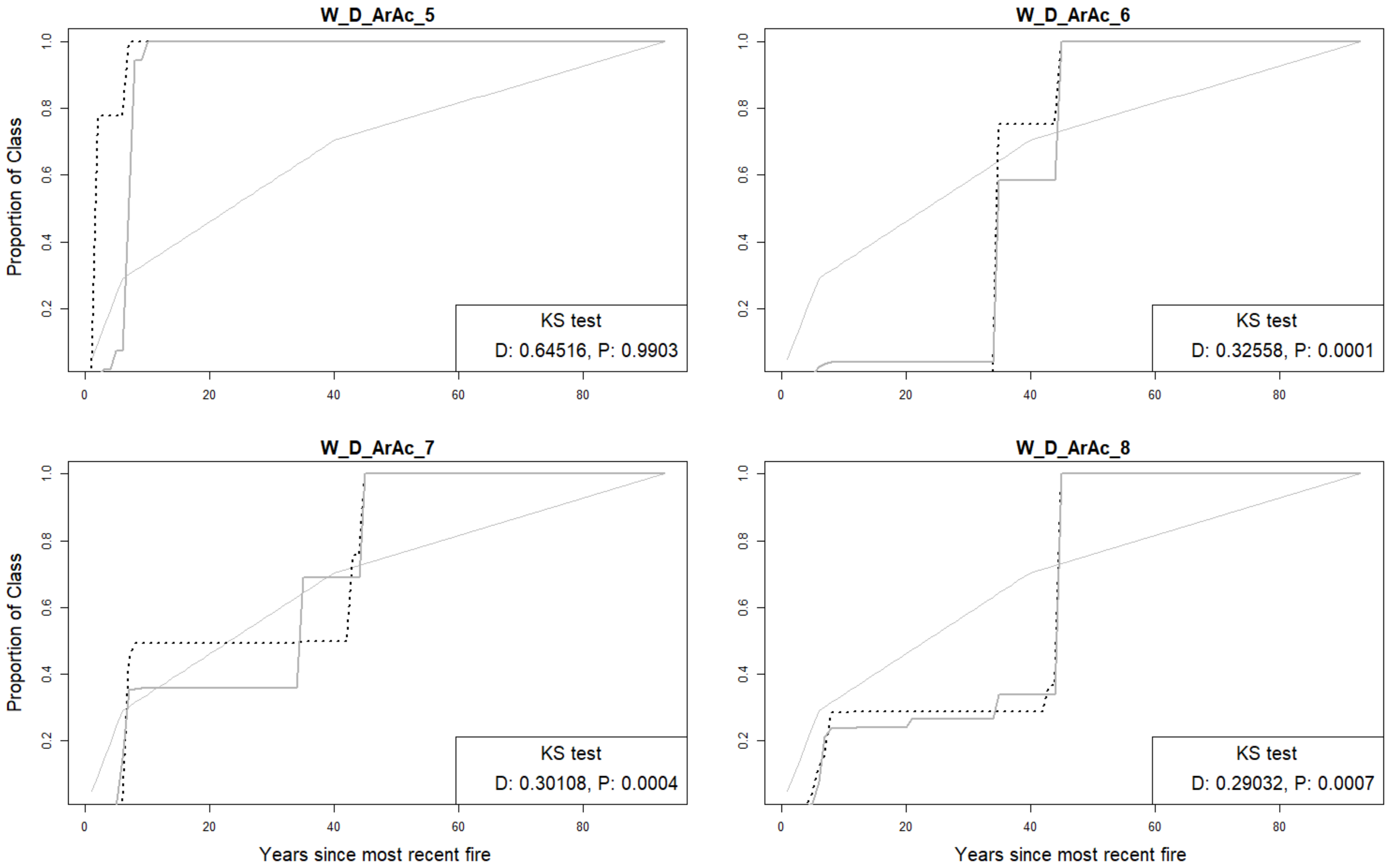
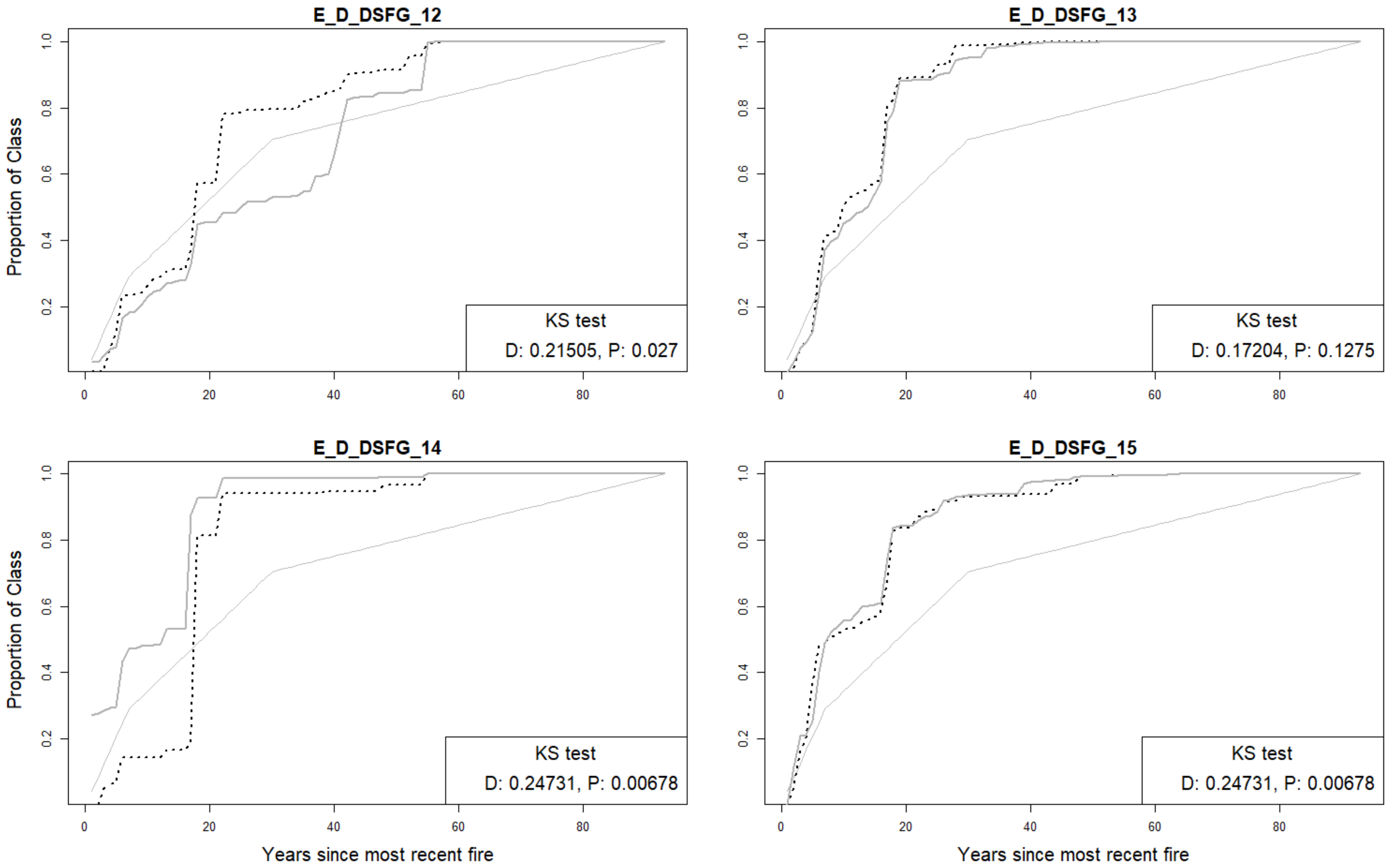
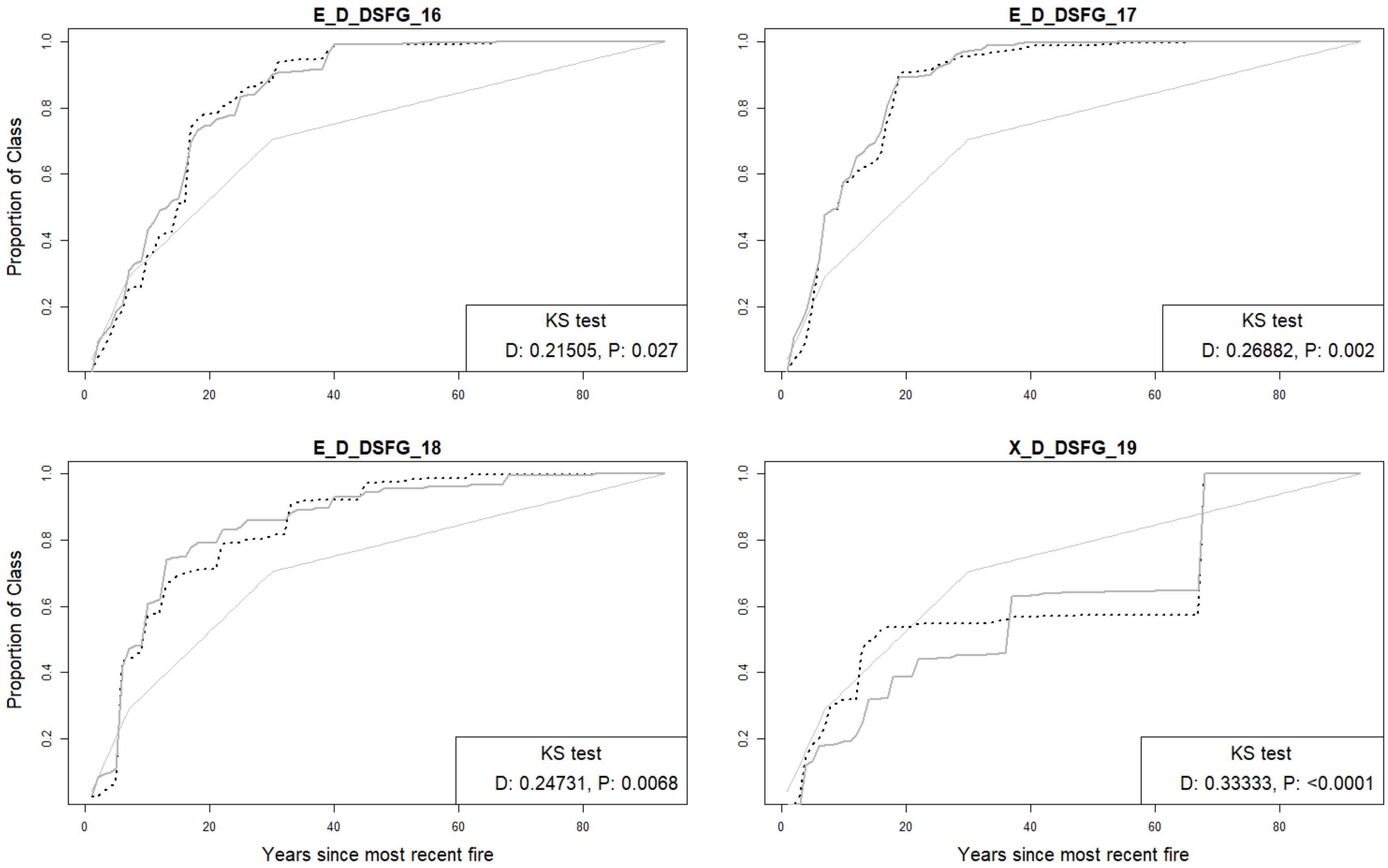
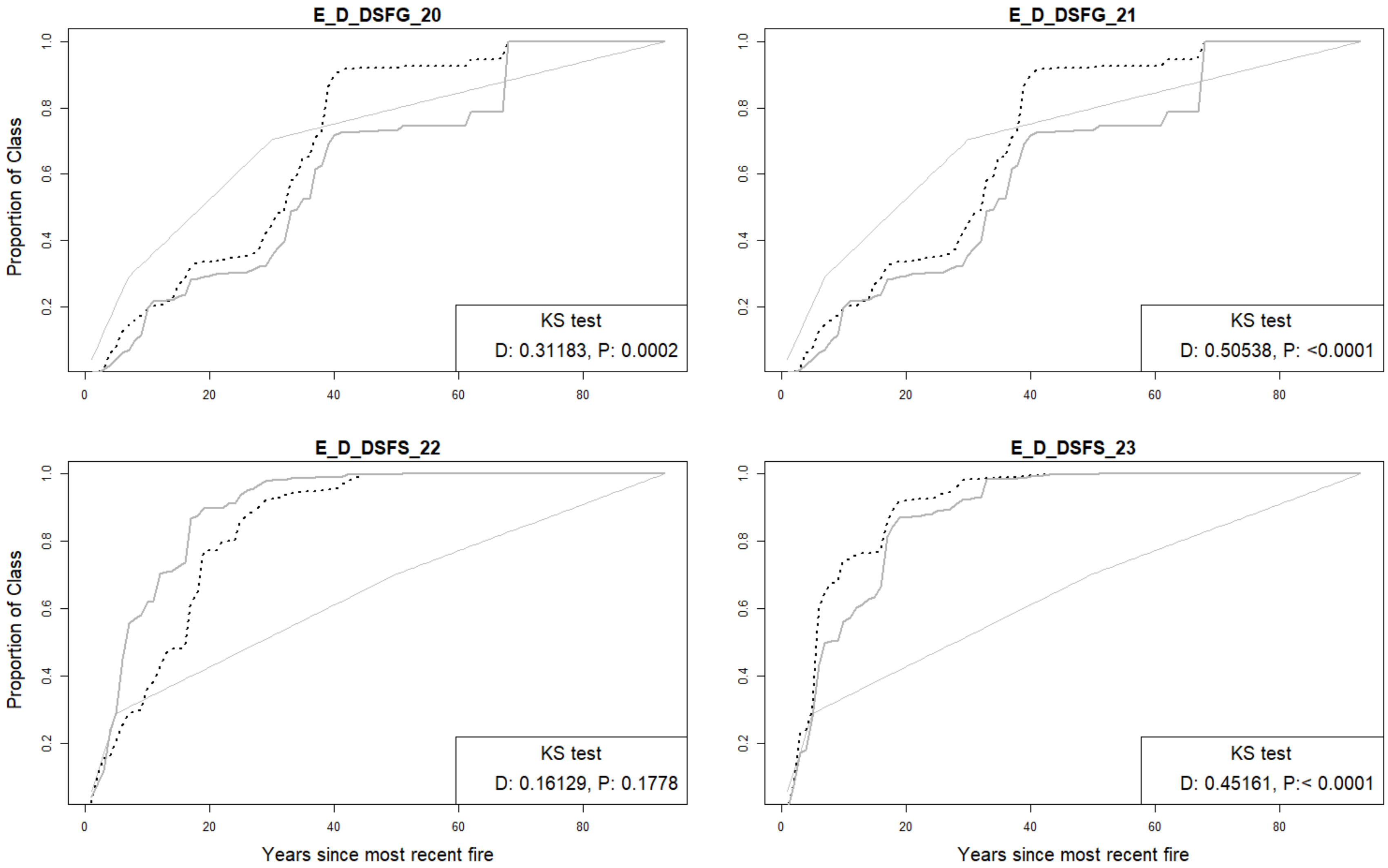


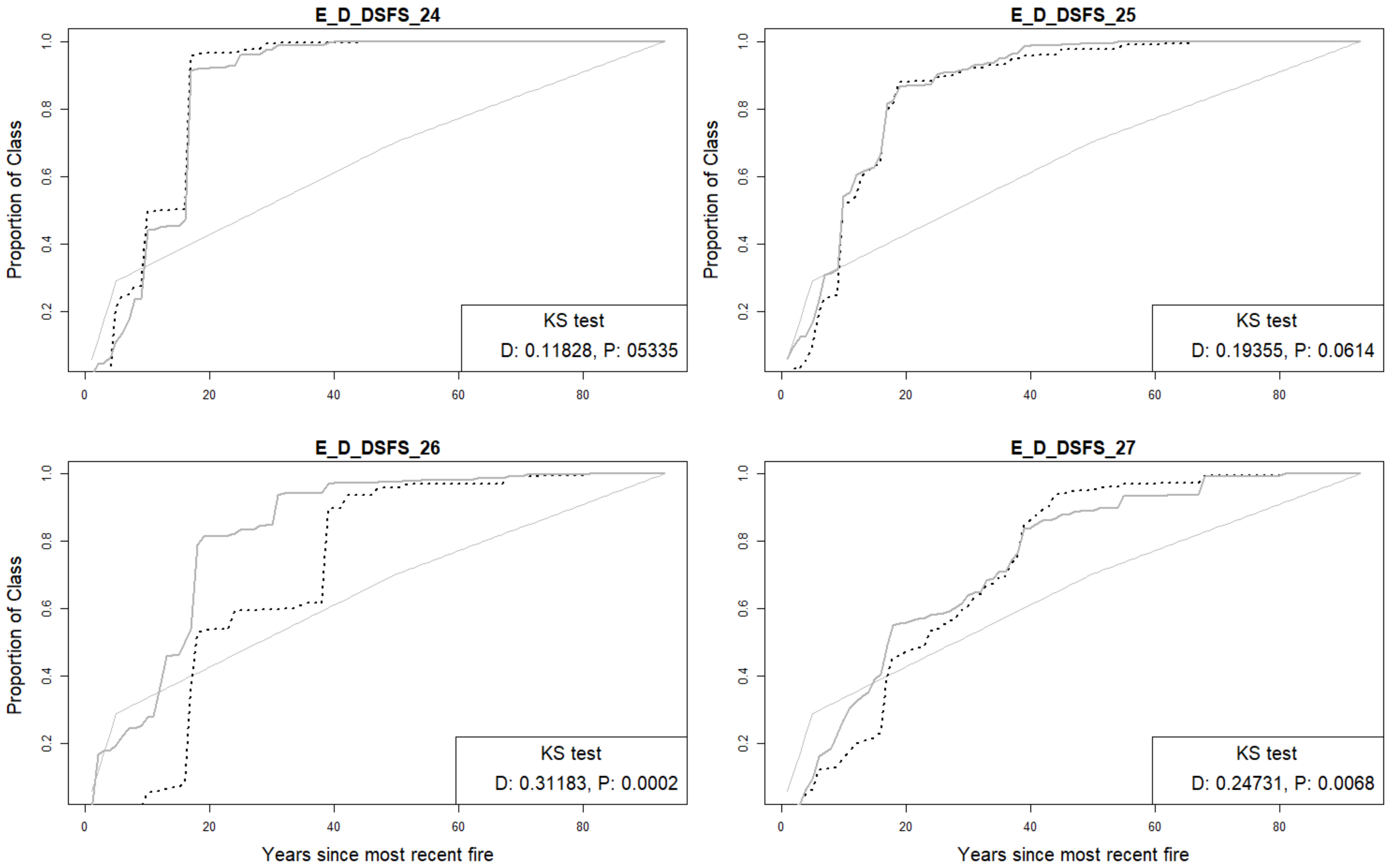
Figure A3.7 Cumulative proportion of most recent fires in each year of known fire history from 1998 to 1902 for each vegetation class within the NPWS_LMZ portion of each formation in NSW. The thick black line represents an even distribution

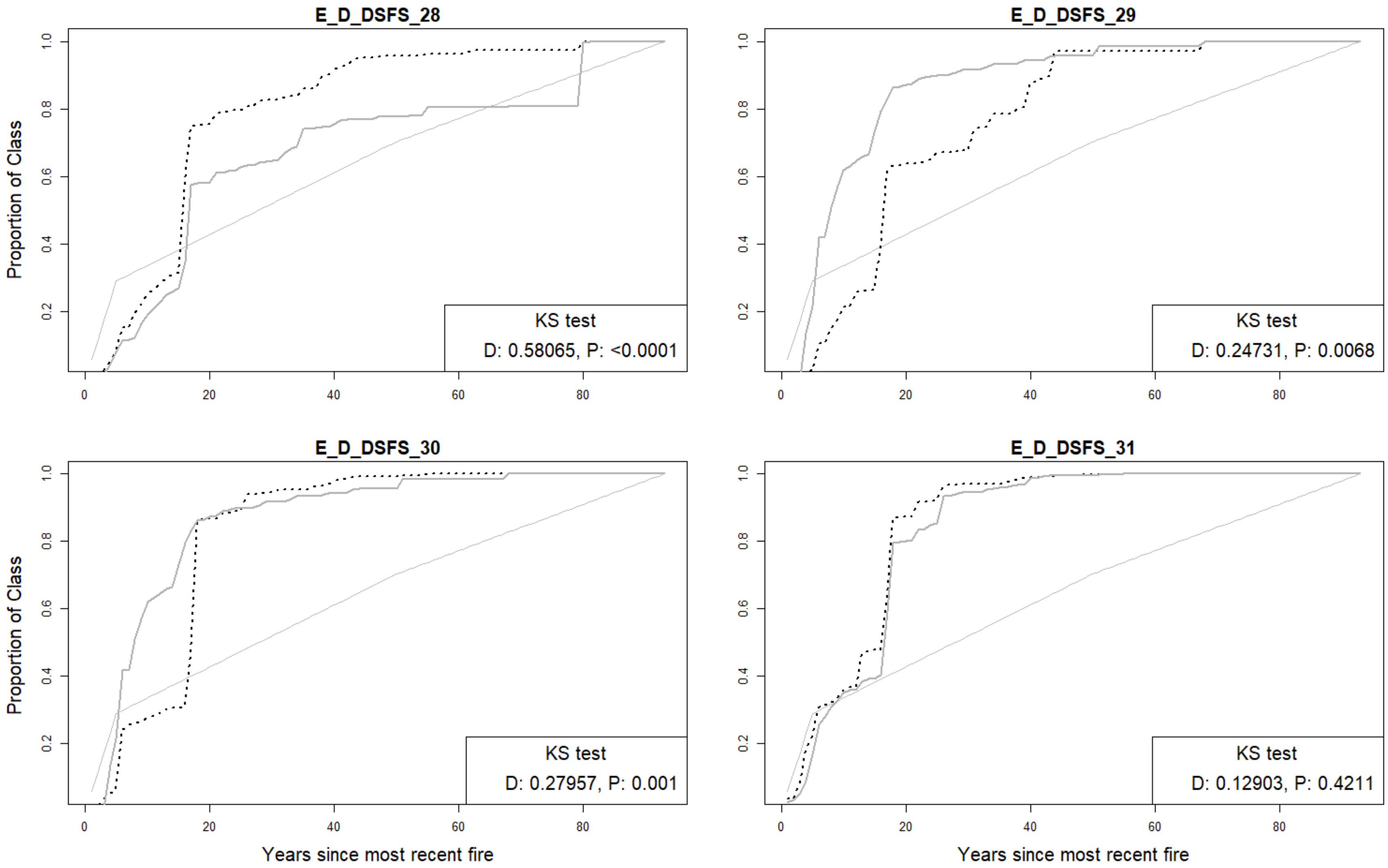

W_D_ArAc_5
KS test
D: 0.64516, P: 0.9903
W_D_ArAc_6
KS test
D: 0.32558, P: 0.0001
W_D_ArAc_7
KS test
D: 0.30108, P: 0.0004
W_D_ArAc_8
KS test
D: 0.29032, P: 0.0007
Proportion of Class
Years since most recent fire
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80

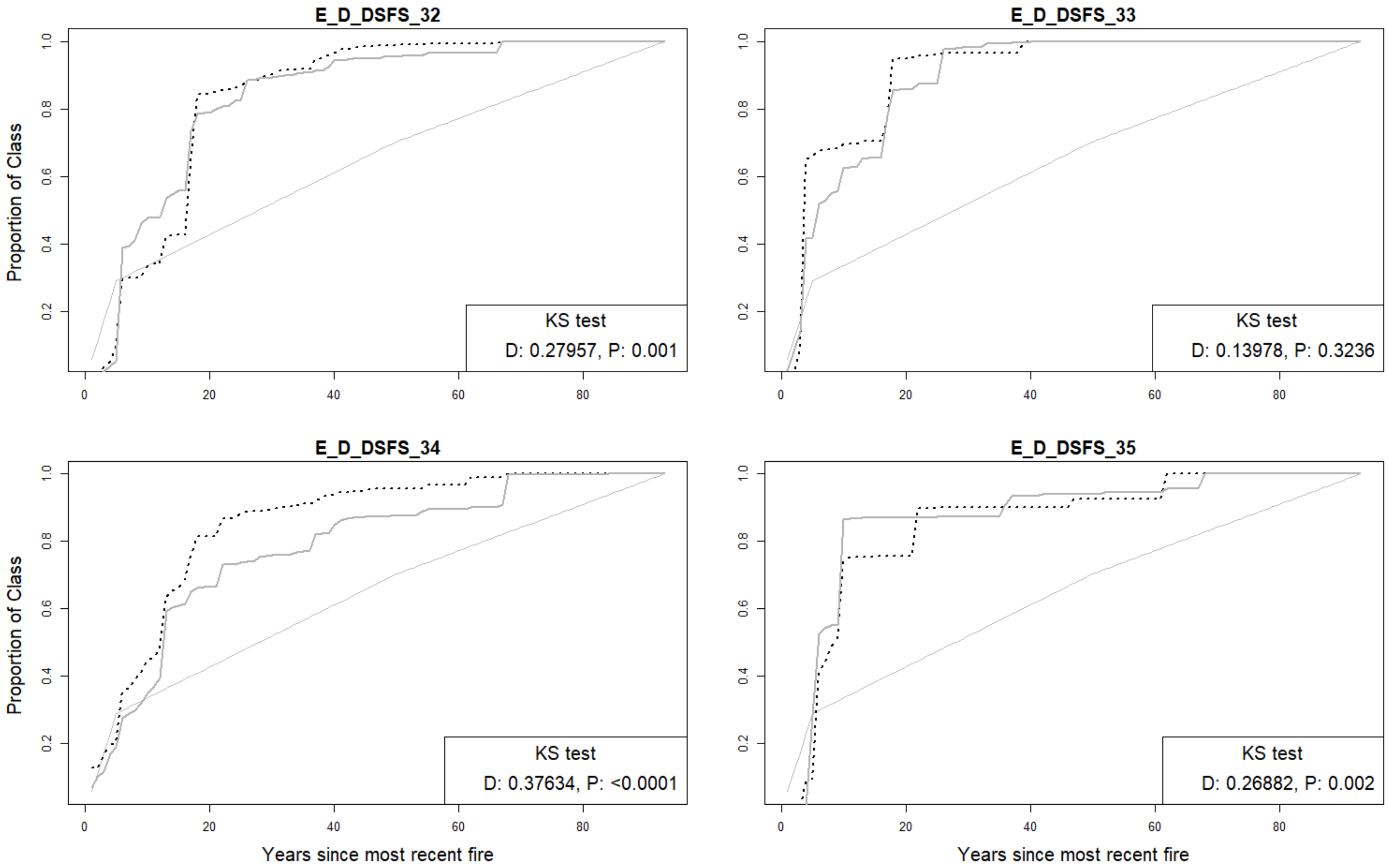

E_D_DSFG_12
KS test
D: 0.21505, P: 0.027
E_D_DSFG_13
KS test
D: 0.17204, P: 0.1275
E_D_DSFG_14
KS test
D: 0.24731, P: 0.00678
E_D_DSFG_15
KS test
D: 0.24731, P: 0.00678
Proportion of Class
Years since most recent fire
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80

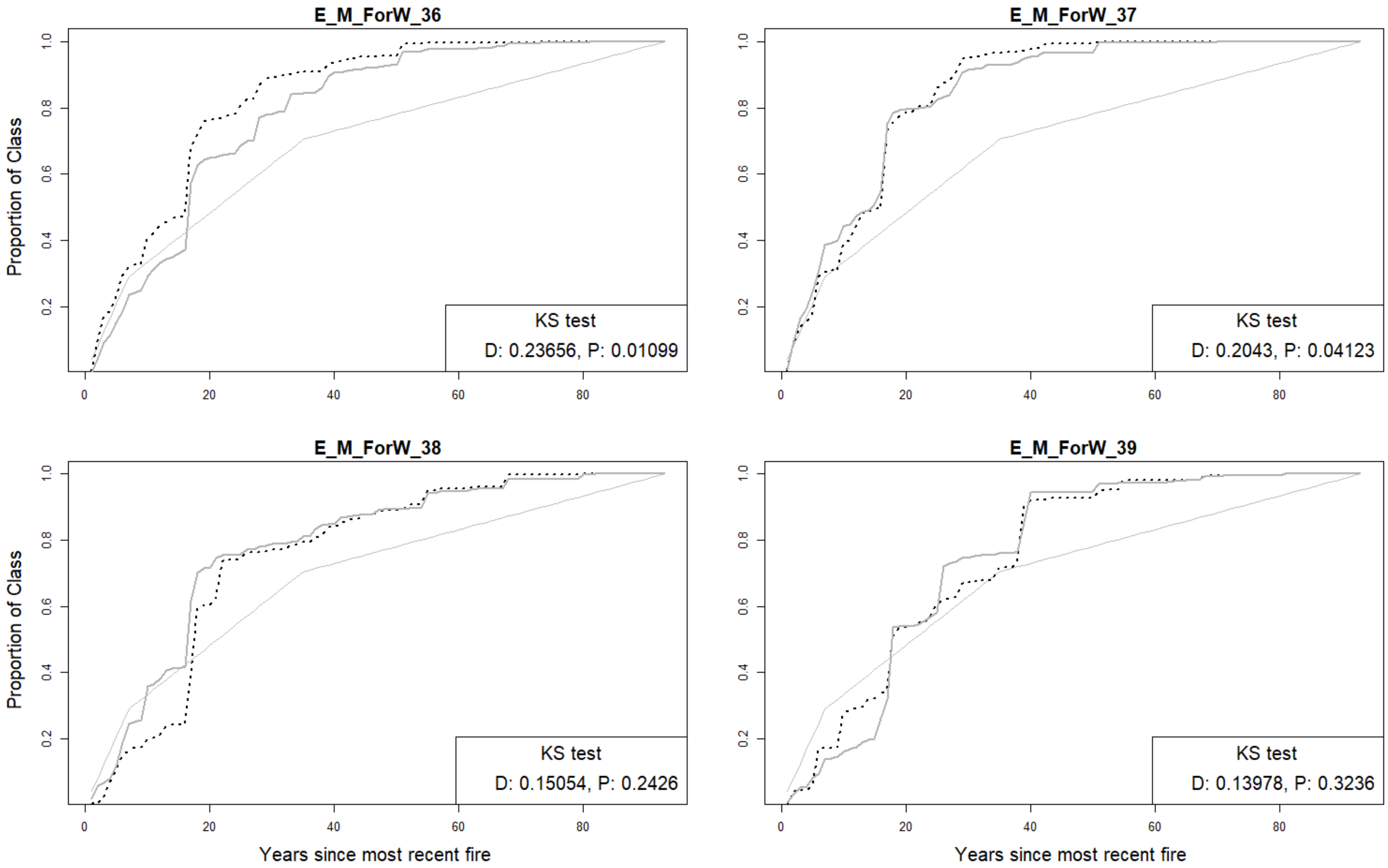

E_D_DSFG_16
Proportion of Class
KS test
D: 0.21505, P: 0.027
E_D_DSFG_17
KS test
D: 0.26882, P: 0.002
E_D_DSFG_18
Proportion of Class
KS test
D: 0.24731, P: 0.0068
Years since most recent fire
X_D_DSFG_19
KS test
D: 0.33333, P: <0.0001
Years since most recent fire

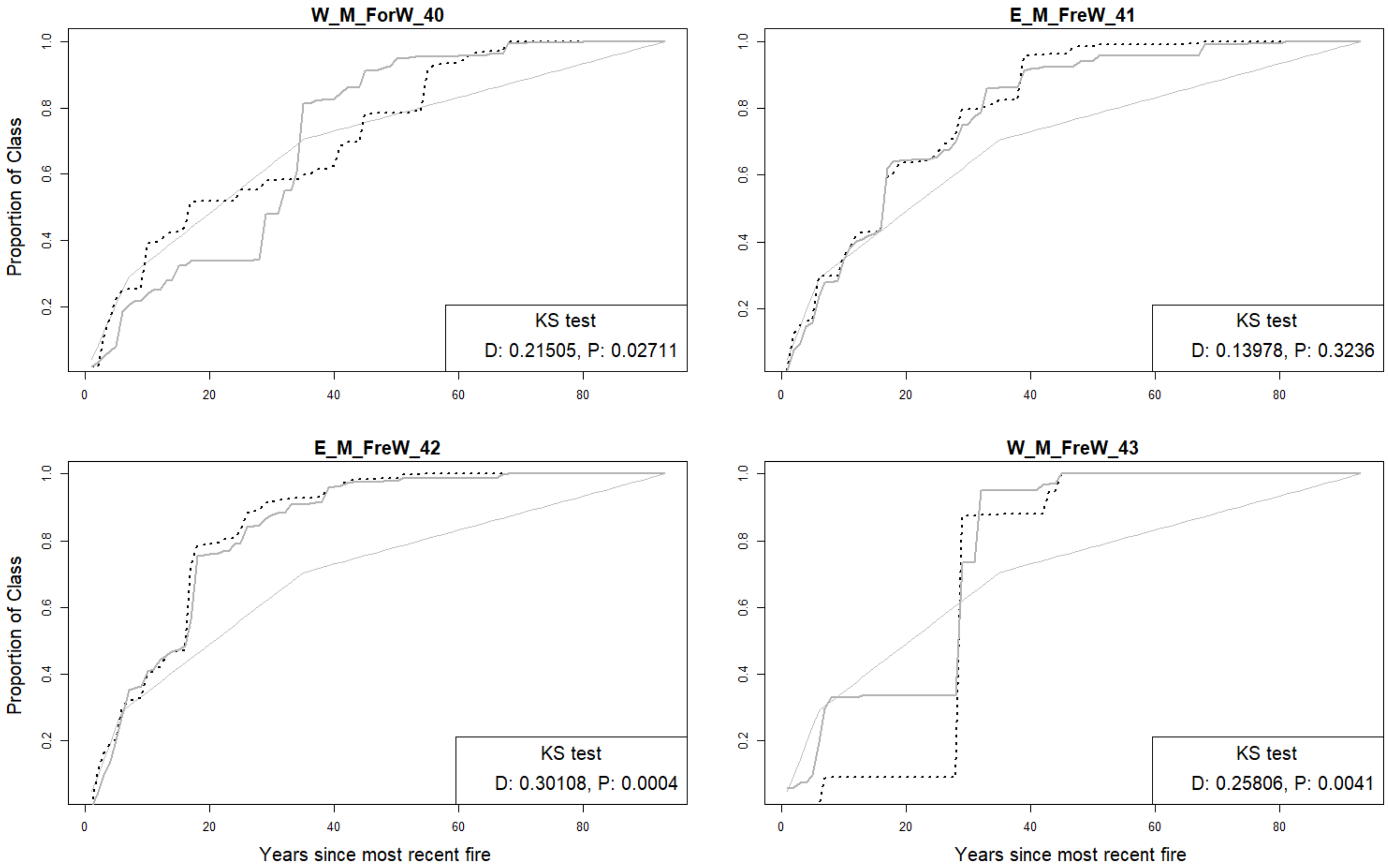

E_D_DSFG_20
E_D_DSFG_21
E_D_DSFS_22
E_D_DSFS_23
Proportion of Class
Years since most recent fire
KS test
D: 0.31183, P: 0.0002
KS test
D: 0.50538, P: <0.0001
KS test
D: 0.16129, P: 0.1778
KS test
D: 0.45161, P:< 0.0001

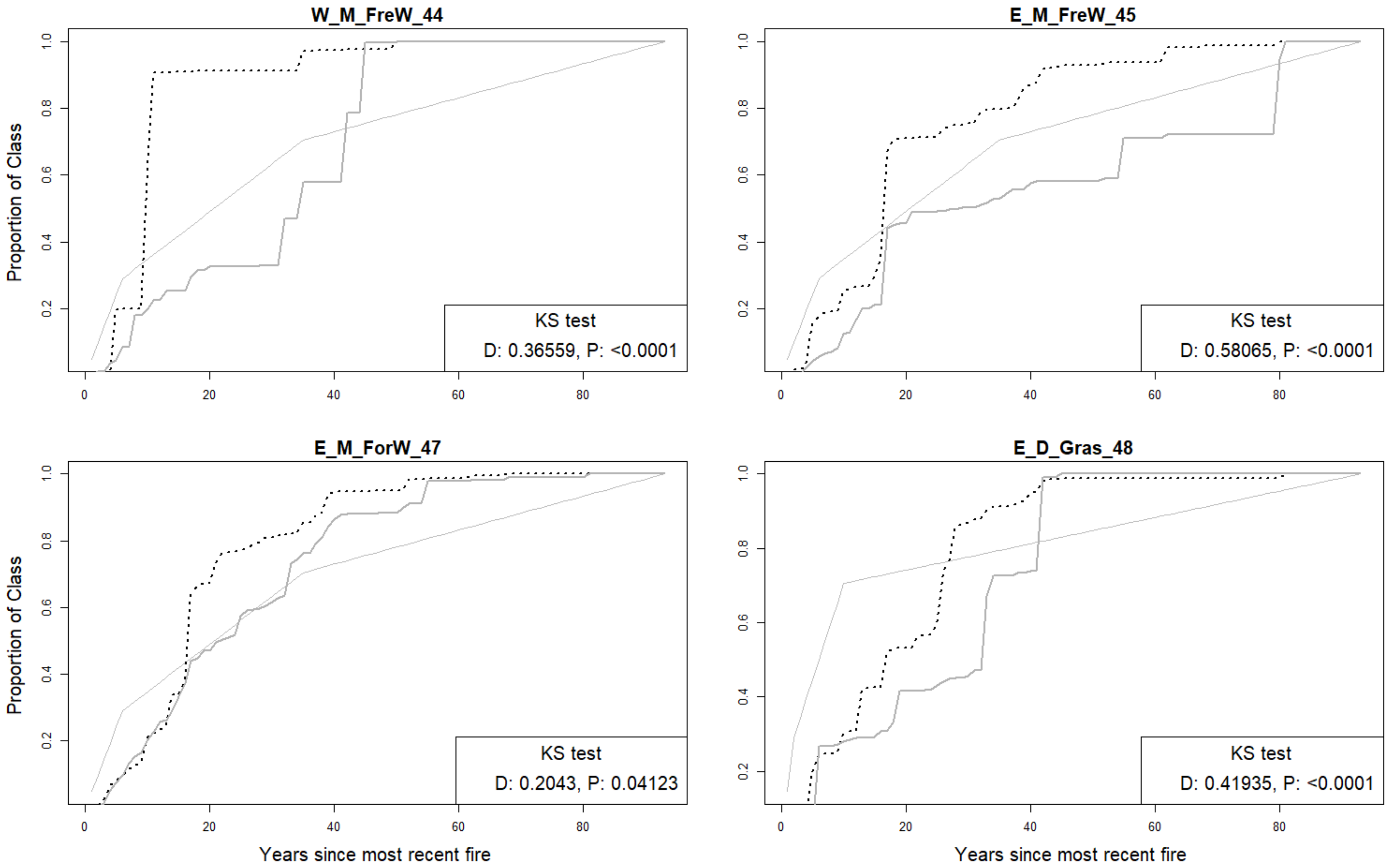

E_D_DSFS_24
KS test
D: 0.11828, P: 05335
E_D_DSFS_25
KS test
D: 0.19355, P: 0.0614
E_D_DSFS_26
KS test
D: 0.31183, P: 0.0002
E_D_DSFS_27
KS test
D: 0.24731, P: 0.0068
Proportion of Class
Years since most recent fire

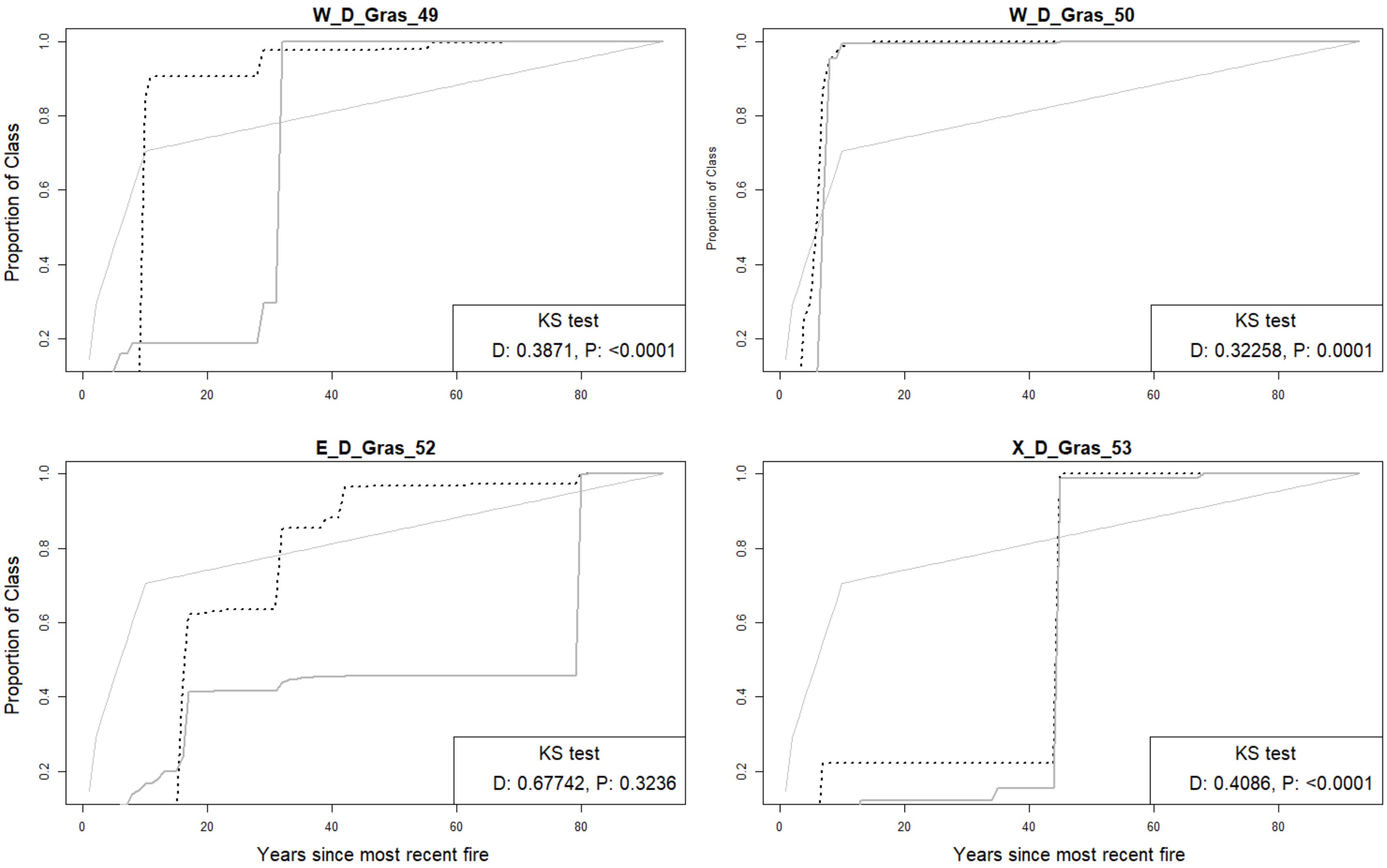

E_D_DSFS_28
E_D_DSFS_29
E_D_DSFS_30
E_D_DSFS_31
Proportion of Class
Years since most recent fire
KS test
D: 0.58065, P: <0.0001
KS test
D: 0.24731, P: 0.0068
KS test
D: 0.27957, P: 0.001
KS test
D: 0.12903, P: 0.4211

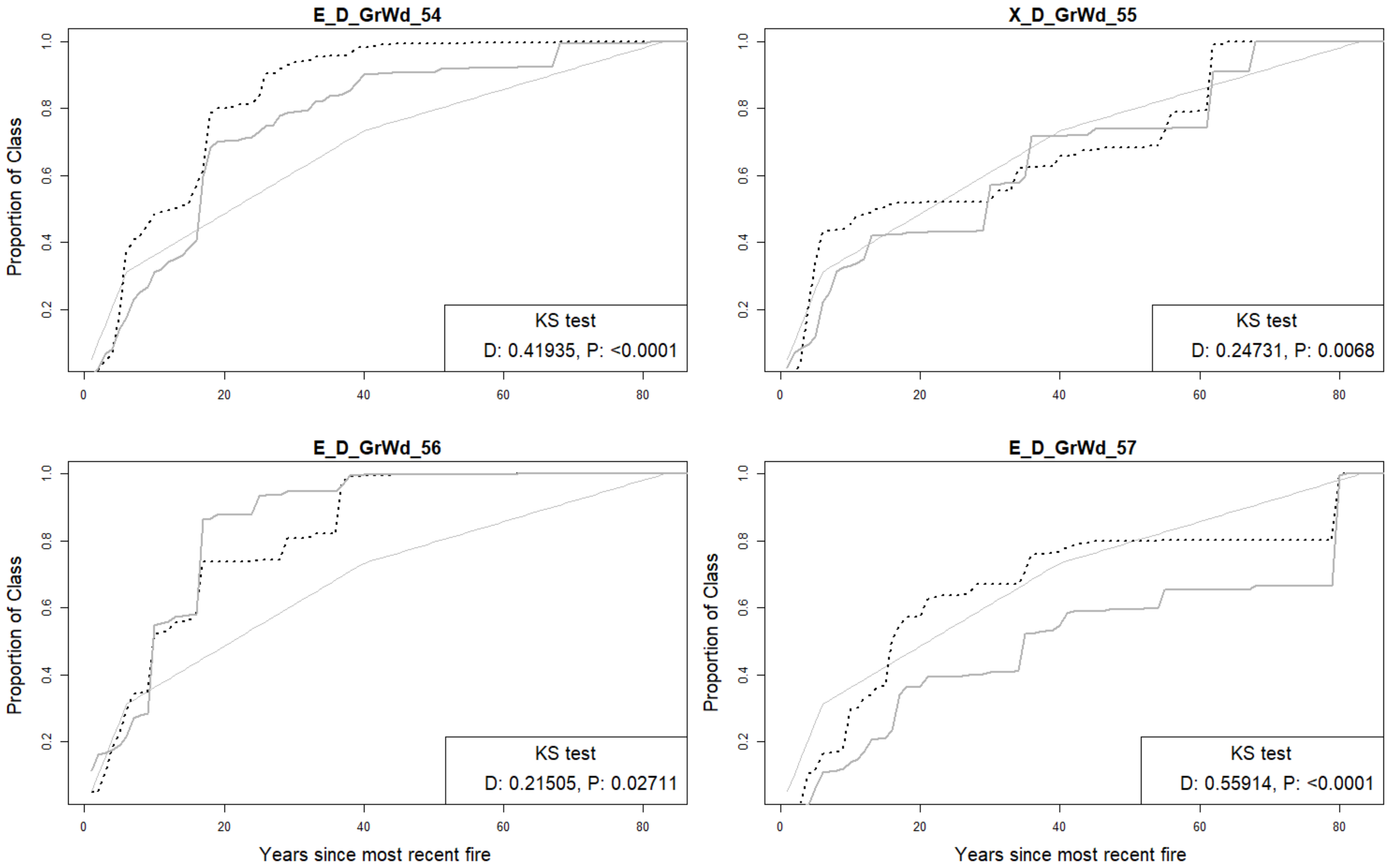

E_D_DSFS_32
KS test
D: 0.27957, P: 0.001
E_D_DSFS_33
KS test
D: 0.13978, P: 0.3236
E_D_DSFS_34
KS test
D: 0.37634, P: <0.0001
E_D_DSFS_35
KS test
D: 0.26882, P: 0.002
Proportion of Class
Years since most recent fire

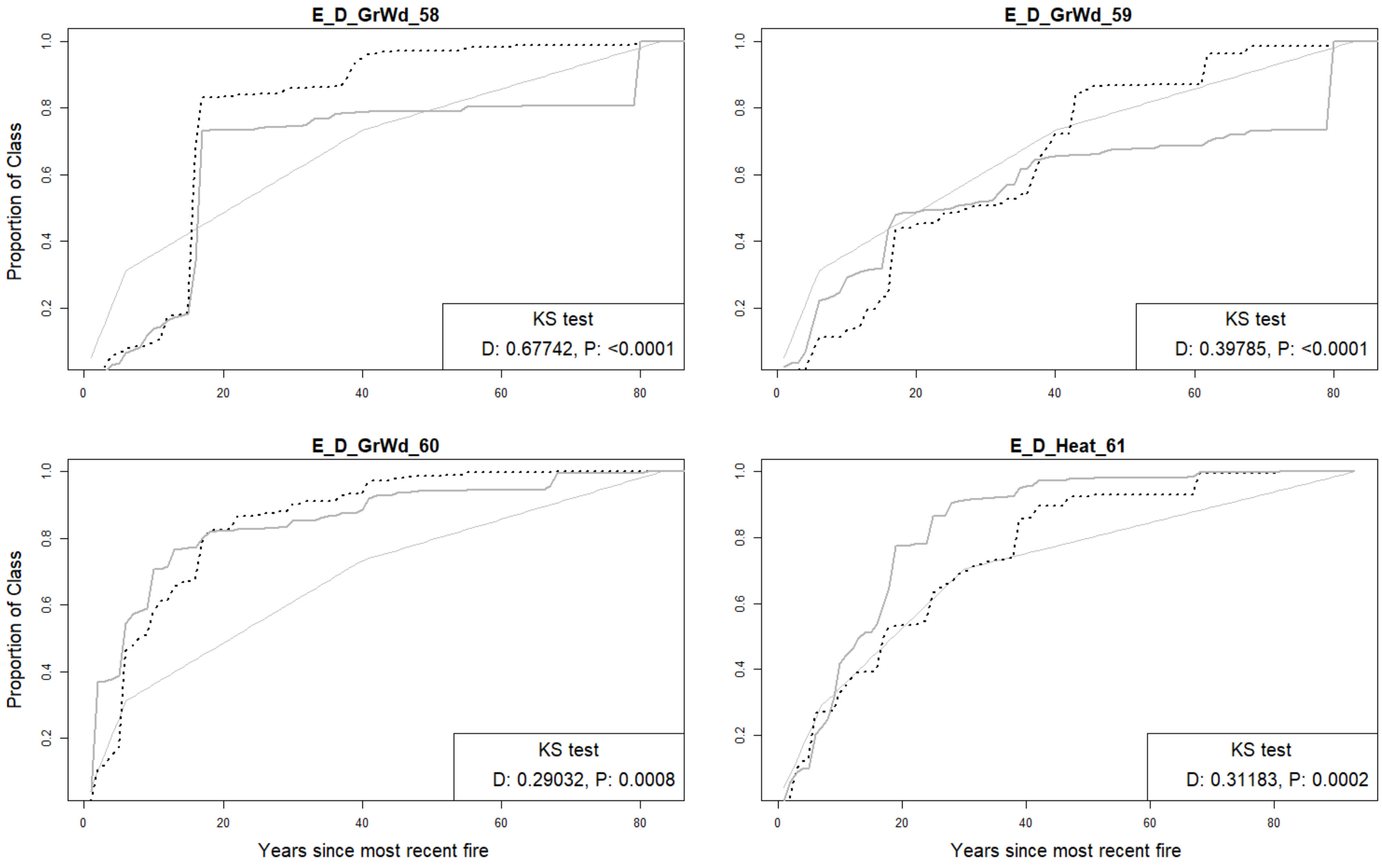

E_M_ForW_36
KS test
D: 0.23656, P: 0.01099
E_M_ForW_37
KS test
D: 0.2043, P: 0.04123
E_M_ForW_38
KS test
D: 0.15054, P: 0.2426
E_M_ForW_39
KS test
D: 0.13978, P: 0.3236
Proportion of Class
Years since most recent fire
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80

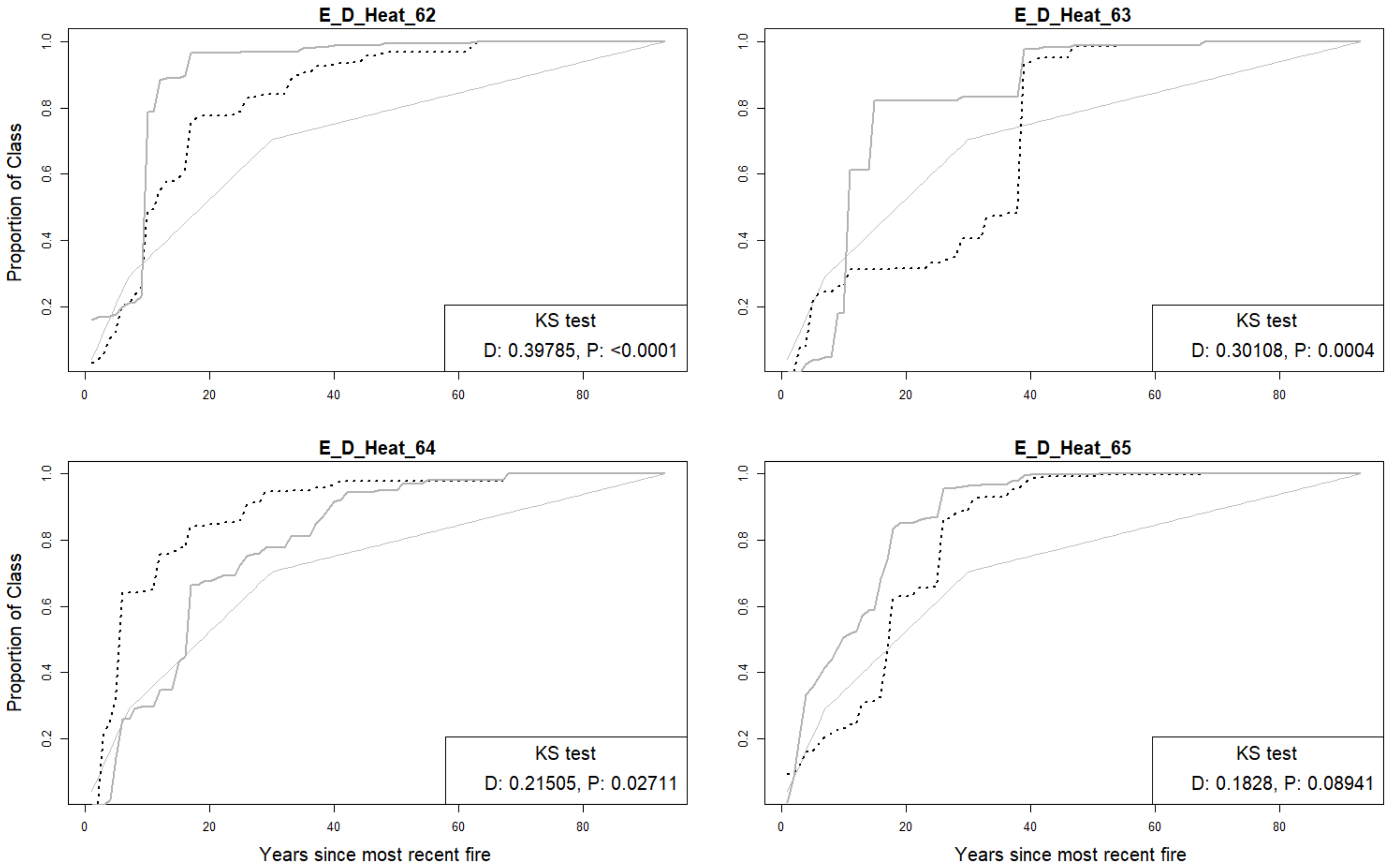

W_M_ForW_40
KS test
D: 0.21505, P: 0.02711
E_M_FreW_41
KS test
D: 0.13978, P: 0.3236
E_M_FreW_42
KS test
D: 0.30108, P: 0.0004
W_M_FreW_43
KS test
D: 0.25806, P: 0.0041
Proportion of Class
Years since most recent fire
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80

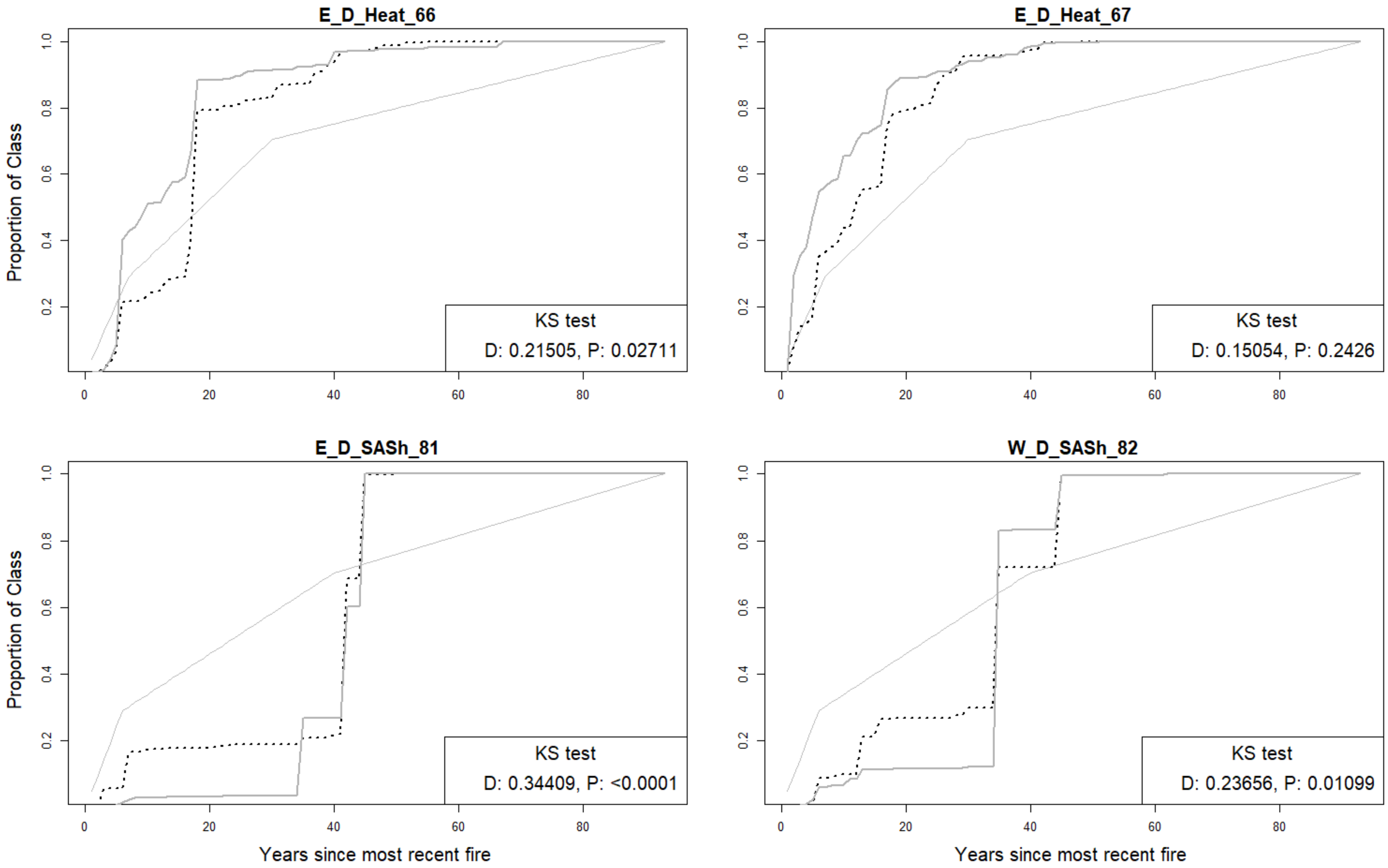

W_M_FreW_44
KS test
D: 0.36559, P: <0.0001
E_M_FreW_45
KS test
D: 0.58065, P: <0.0001
E_M_ForW_47
KS test
D: 0.2043, P: 0.04123
E_D_Gras_48
KS test
D: 0.41935, P: <0.0001
Proportion of Class
Years since most recent fire
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80

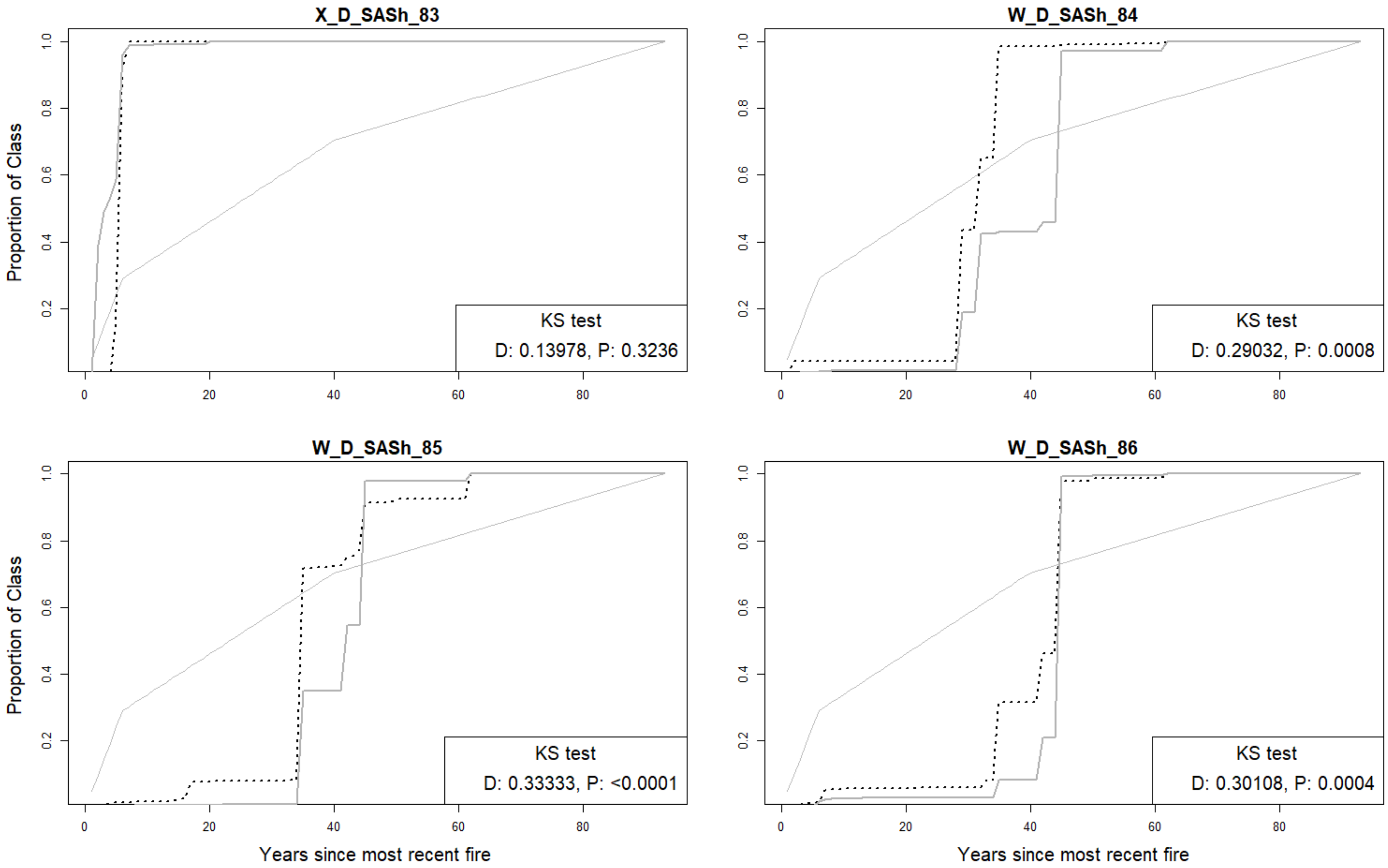

W_D_Gras_49
Proportion of Class
KS test
D: 0.3871, P: <0.0001
W_D_Gras_50
Proportion of Class
KS test
D: 0.32258, P: 0.0001
E_D_Gras_52
Proportion of Class
KS test
D: 0.67742, P: 0.3236
Years since most recent fire
X_D_Gras_53
KS test
D: 0.4086, P: <0.0001
Years since most recent fire

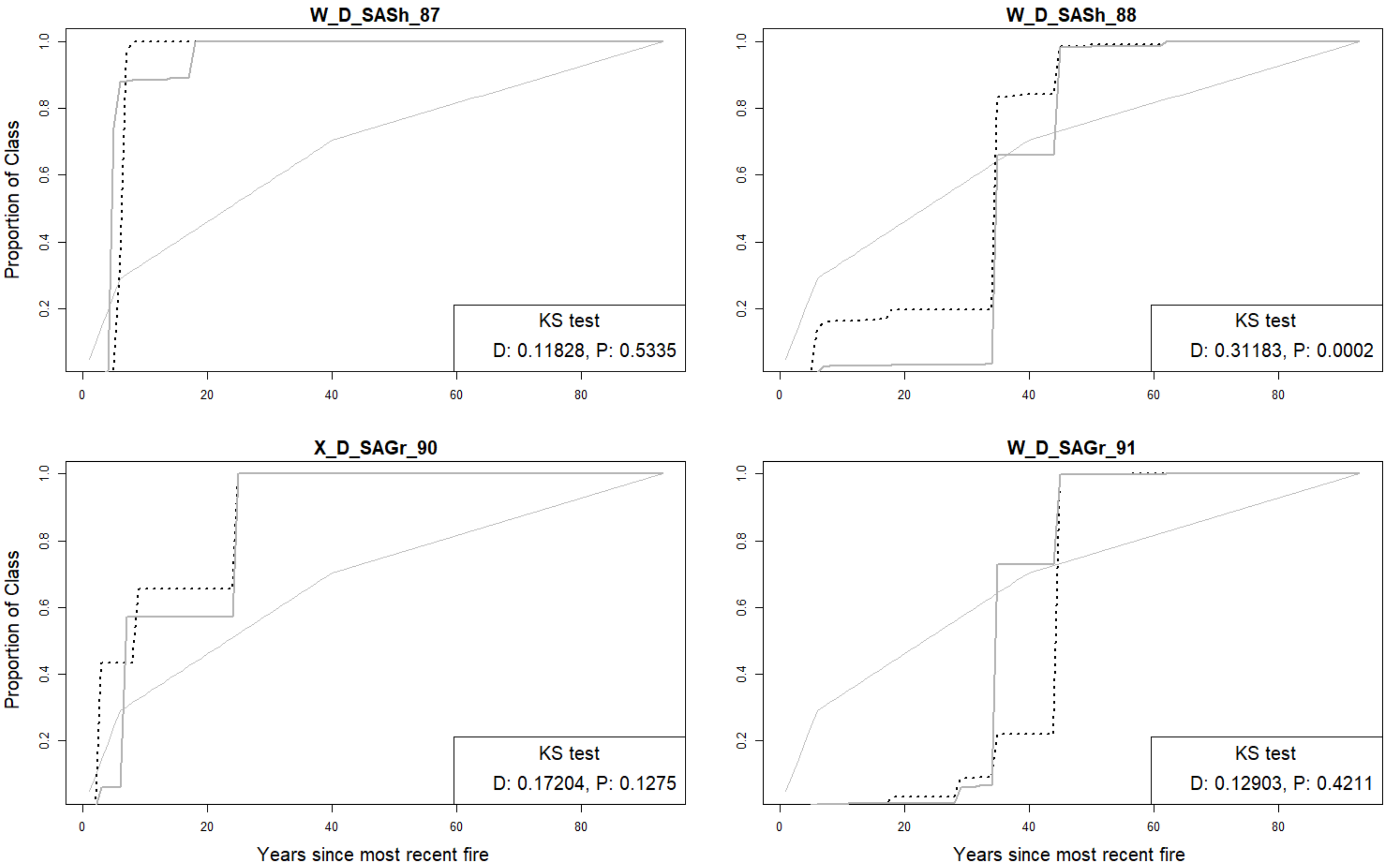

E_D_GrWd_54
X_D_GrWd_55
E_D_GrWd_56
E_D_GrWd_57
Proportion of Class
Years since most recent fire
KS test
D: 0.41935, P: <0.0001
D: 0.24731, P: 0.0068
D: 0.21505, P: 0.02711
D: 0.55914, P: <0.0001

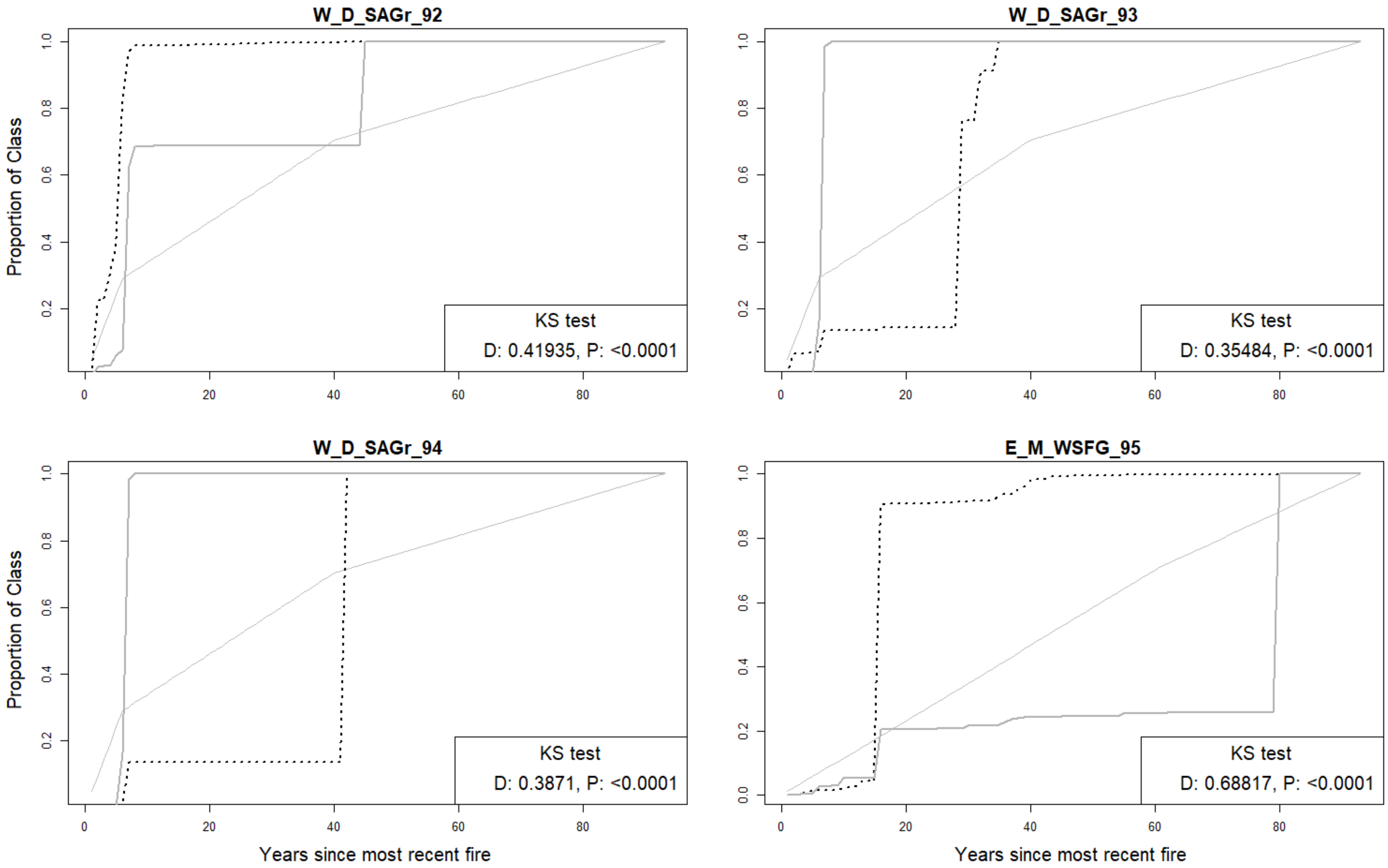

E_D_GrWd_58
KS test
D: 0.67742, P: <0.0001
E_D_GrWd_59
KS test
D: 0.39785, P: <0.0001
E_D_GrWd_60
KS test
D: 0.29032, P: 0.0008
E_D_Heat_61
KS test
D: 0.31183, P: 0.0002
Proportion of Class
Years since most recent fire
0
20
40
60
80
0.2
0.4
0.6
0.8
1.0

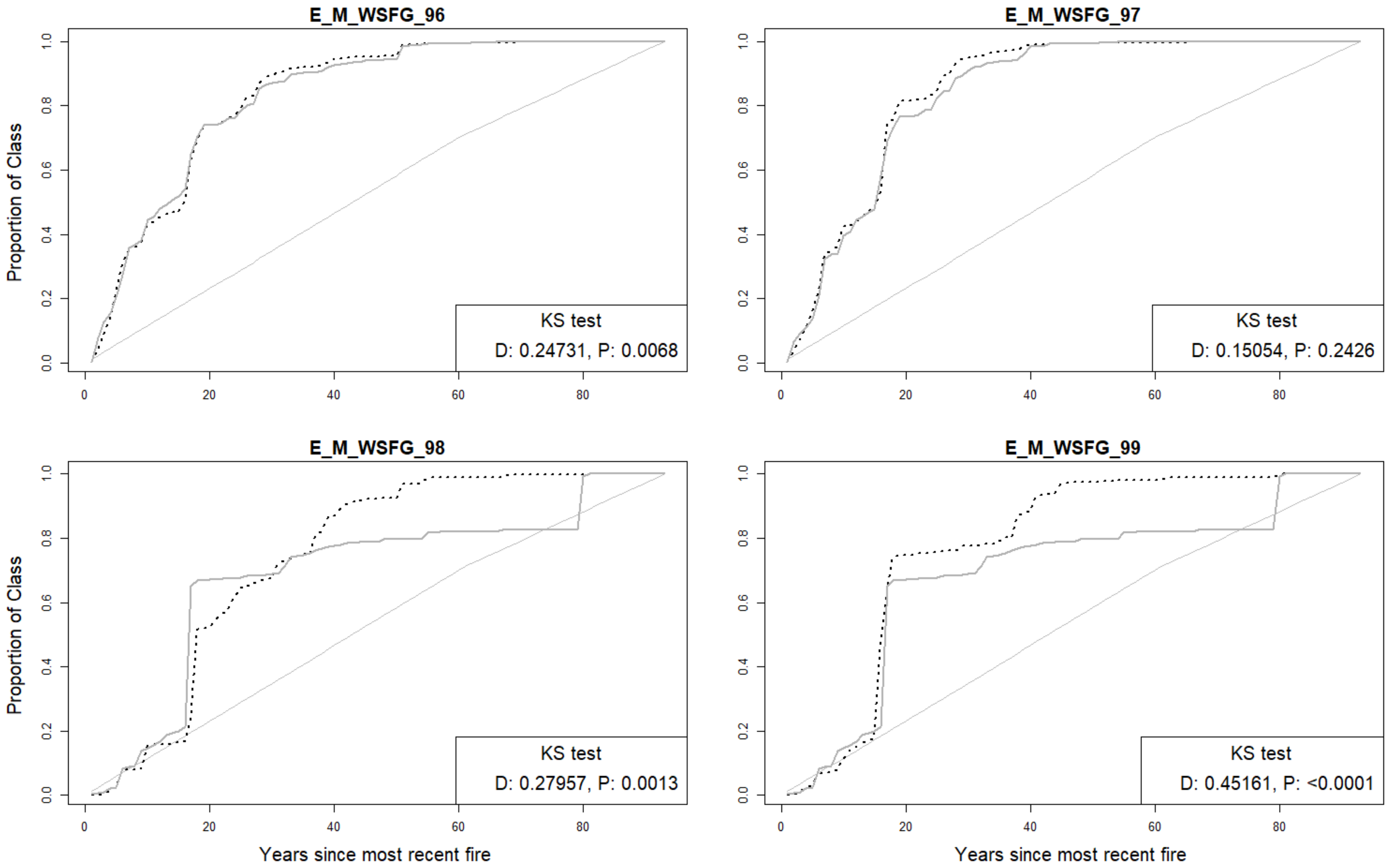

E_D_Heat_62
Proportion of Class
KS test
D: 0.39785, P: <0.0001
E_D_Heat_63
KS test
D: 0.30108, P: 0.0004
E_D_Heat_64
Proportion of Class
KS test
D: 0.21505, P: 0.02711
Years since most recent fire
E_D_Heat_65
KS test
D: 0.1828, P: 0.08941
Years since most recent fire


E_D_Heat_66
Proportion of Class
KS test
D: 0.21505, P: 0.02711
E_D_Heat_67
KS test
D: 0.15054, P: 0.2426
E_D_SASh_81
Proportion of Class
KS test
D: 0.34409, P: <0.0001
Years since most recent fire
W_D_SASh_82
KS test
D: 0.23656, P: 0.01099
Years since most recent fire


X_D_SASh_83
KS test
D: 0.13978, P: 0.3236
W_D_SASh_84
KS test
D: 0.29032, P: 0.0008
W_D_SASh_85
KS test
D: 0.33333, P: <0.0001
W_D_SASh_86
KS test
D: 0.30108, P: 0.0004
Proportion of Class
Years since most recent fire
0
20
40
60
80
0.2
0.4
0.6
0.8
1.0


W_D_SASh_87
KS test
D: 0.11828, P: 0.5335
W_D_SASh_88
KS test
D: 0.31183, P: 0.0002
X_D_SAGr_90
KS test
D: 0.17204, P: 0.1275
W_D_SAGr_91
KS test
D: 0.12903, P: 0.4211
Proportion of Class
Years since most recent fire
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80


W_D_SAGr_92
W_D_SAGr_93
W_D_SAGr_94
E_M_WSFG_95
Proportion of Class
Proportion of Class
KS test
D: 0.41935, P: <0.0001
KS test
D: 0.35484, P: <0.0001
KS test
D: 0.3871, P: <0.0001
KS test
D: 0.68817, P: <0.0001
Years since most recent fire
Years since most recent fire



E_M_WSFG_96
KS test
D: 0.24731, P: 0.0068
E_M_WSFG_97
KS test
D: 0.15054, P: 0.2426
E_M_WSFG_98
KS test
D: 0.27957, P: 0.0013
E_M_WSFG_99
KS test
D: 0.45161, P: <0.0001
Proportion of Class
Years since most recent fire

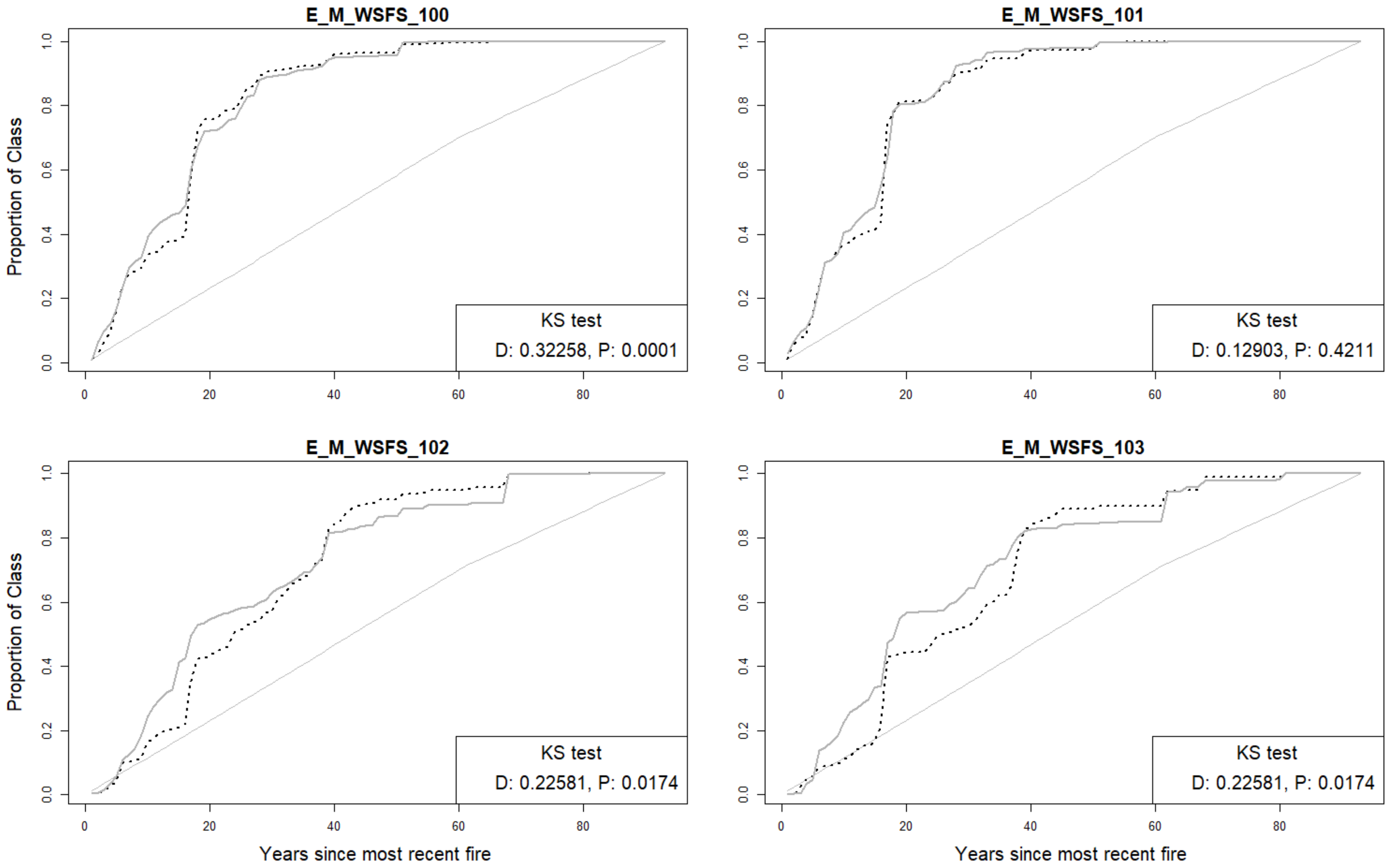


Figure A3.8 The D-test statistics and significance value (P) of a Kolmogorov-Smirnov test (ks.test; R Core Team, 2020) of distributions of cumulative proportion of most recent fires in each year of known fire history from 2018 to 1926 between the NPWS_LMZ portion and the non-NPWS portion of each vegetation class in NSW

Appendix 4: Supplementary materials for Chapter Five

Additional effects plots for the best and alternate GLM models for each of the response variables at a site and quadrat level, not shown in Chapter 5 (see Chapter 5.3.3; Table 5.4; Table 5.5).

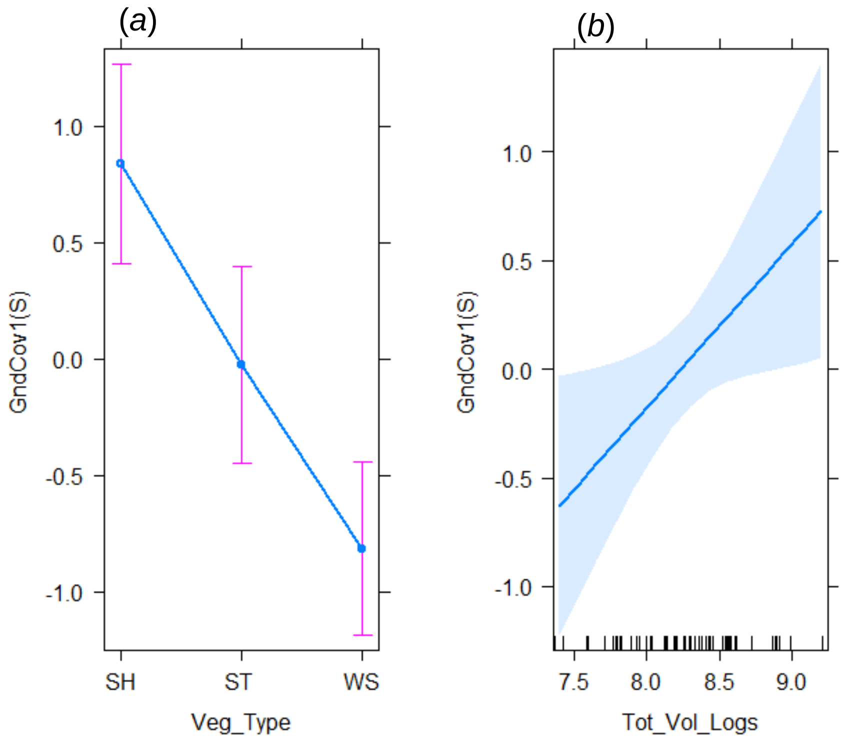


Figure A4.1: Effects plot for the alternate GLM for GndCov1(S): (*a*) vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes); and (*b*) the total volume on a site. Explanations of the principal components are in Table 5.3

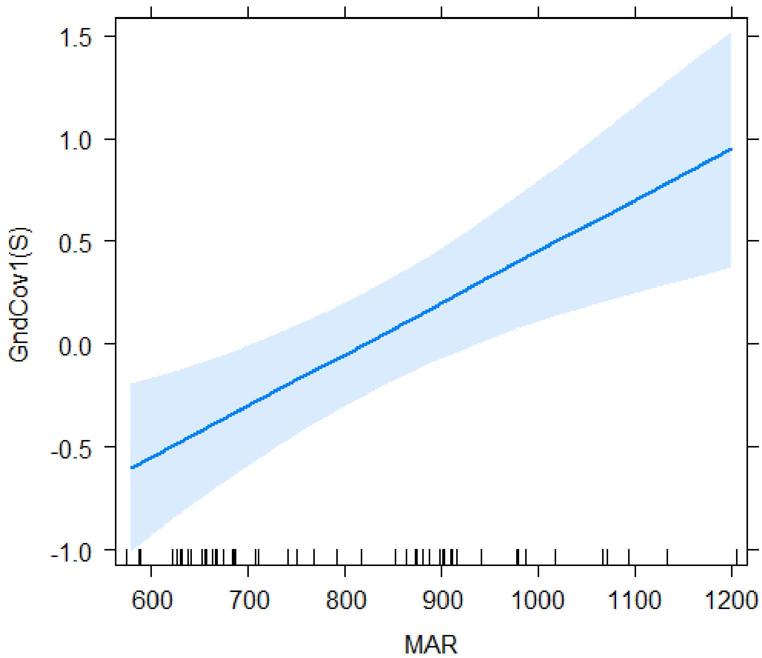


Figure A4.2: Effects plot for the alternate GLM for GndCov1(S) showing mean annual rainfall (MAR, mm) as the best predictor. Explanations of the principal components are in Table 5.3

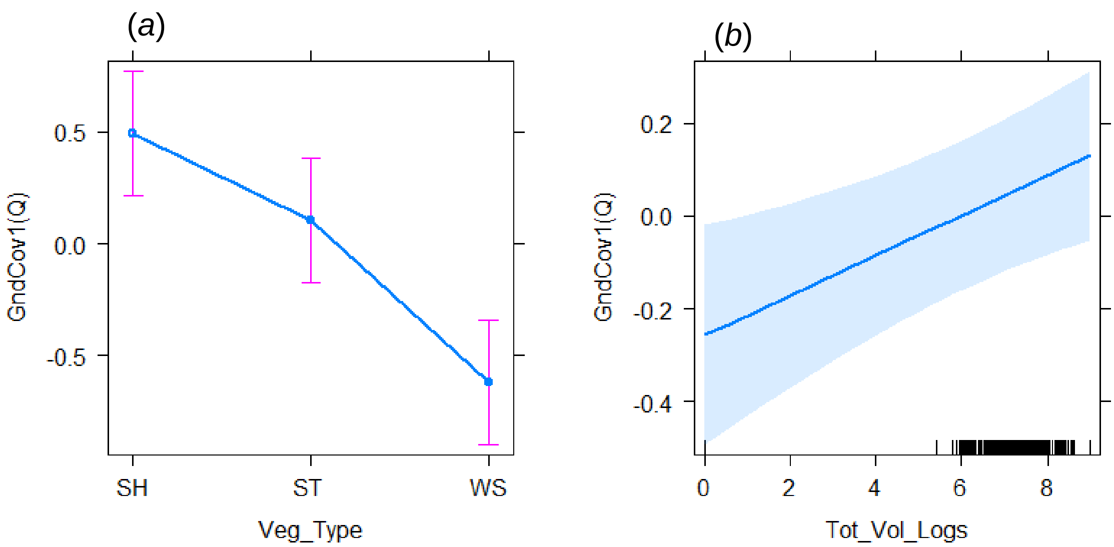


Figure A4.3: Effects plot for the alternate GLM for GndCov1(Q): (*a*) vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes); and (*b*) total volume (cm^3) of logs in a quadrat. Explanations of the principal components are in Table 5.3

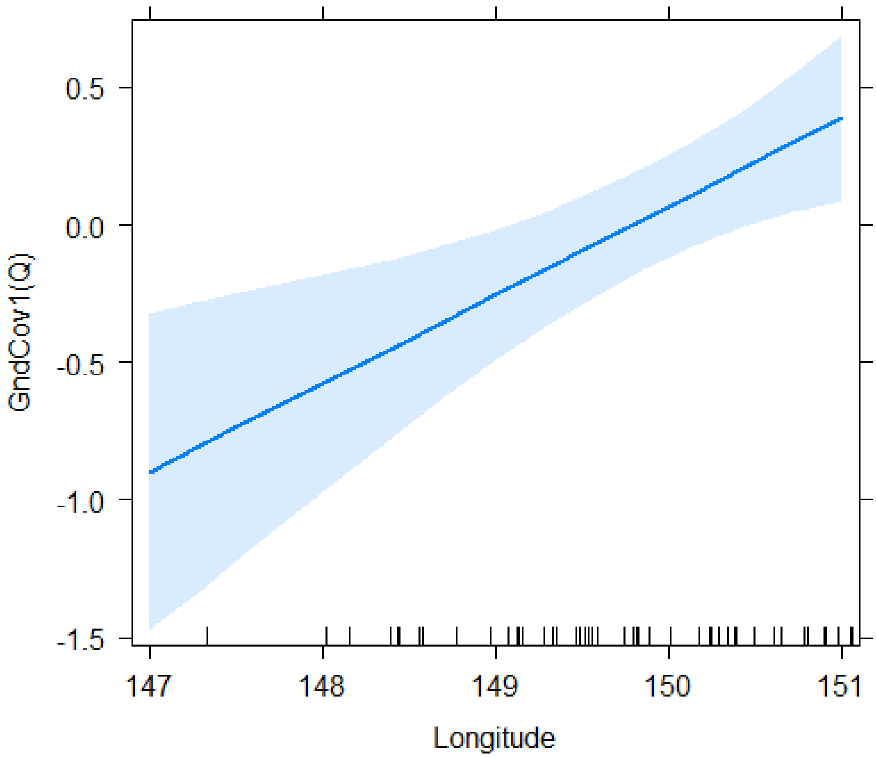


Figure A4.4: Effects plot for the alternate GLM for GndCov1(Q) showing longitude as the best predictor. Explanations of the principal components are in Table 5.3

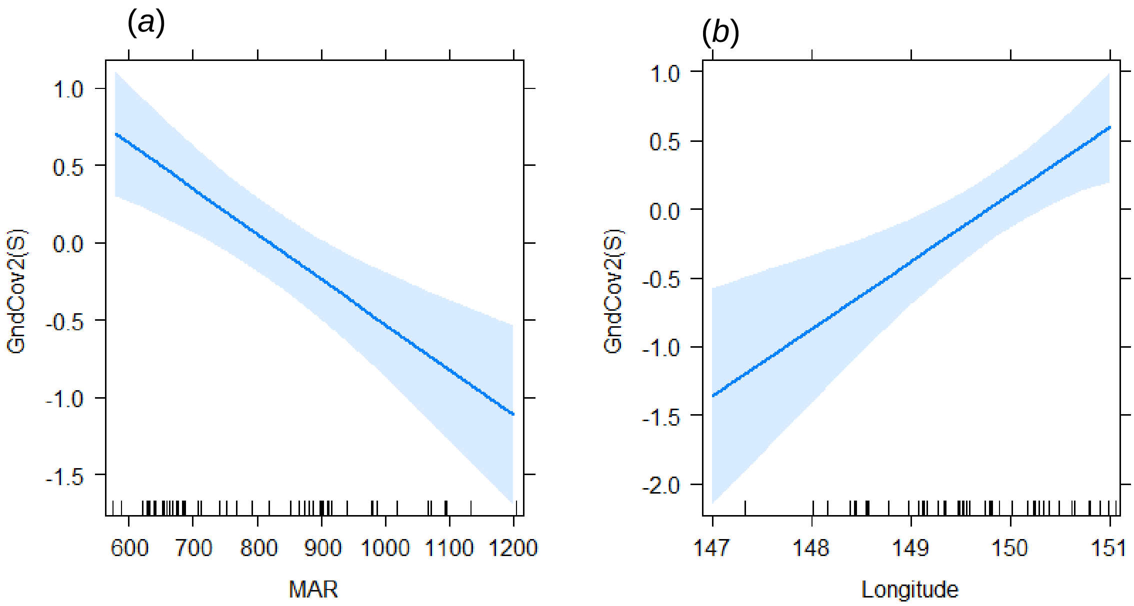


Figure A4.5: Effects plot for the alternate GLM for GndCov2(S): (*a*) mean annual rainfall (MAR, mm); and (*b*) longitude. Explanations of the principal components are in Table 5.3

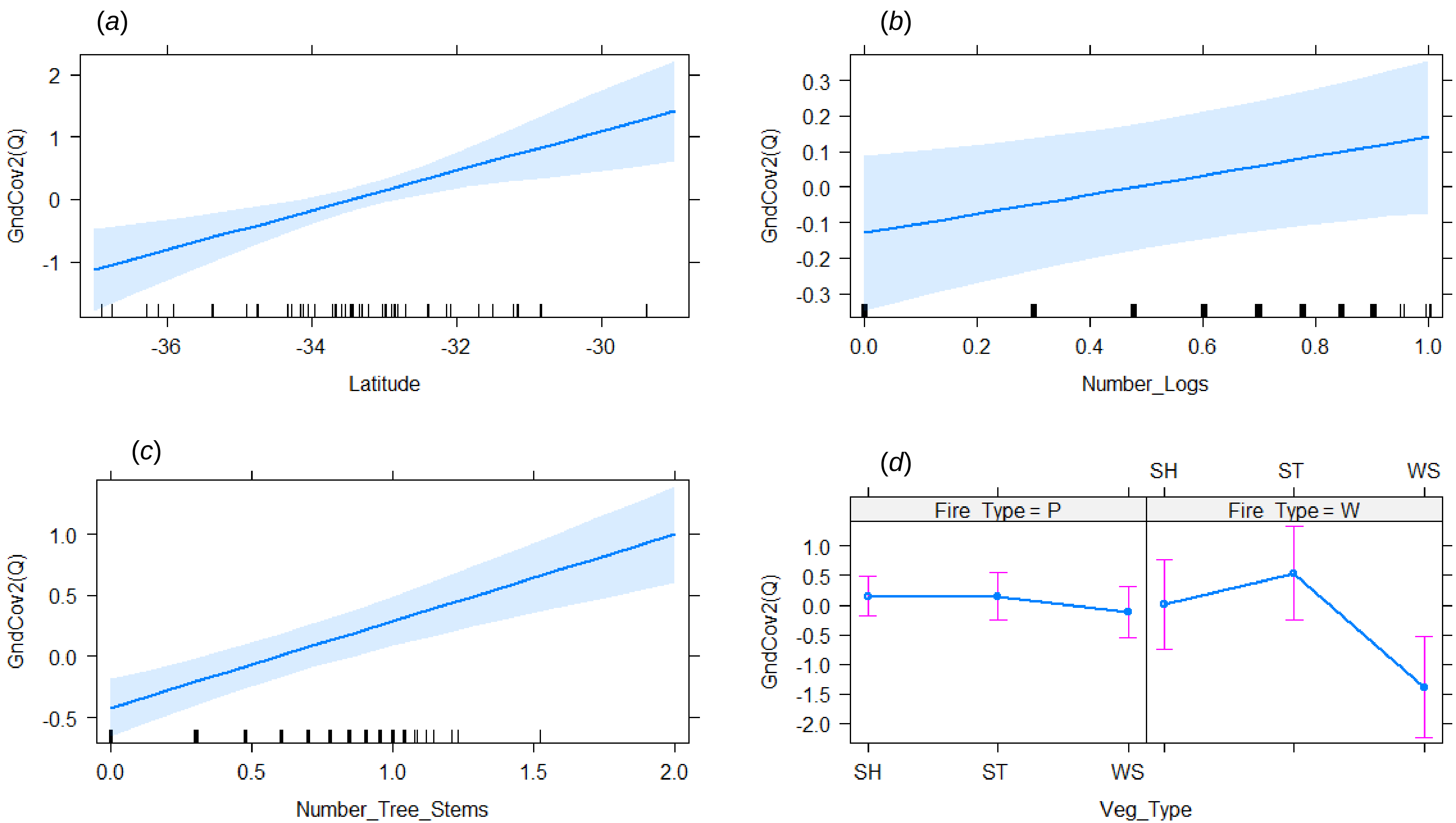


Figure A4.6: Effects plot for the best GLM for GndCov2(Q): (*a*) latitude; (*b*) the number of logs in a quadrat; (*c*) the number of tree stems in a quadrat; and (*d*) vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) interacting with fire type (p = prescribed, w = wild). Explanations of the principal components are in Table 5.3

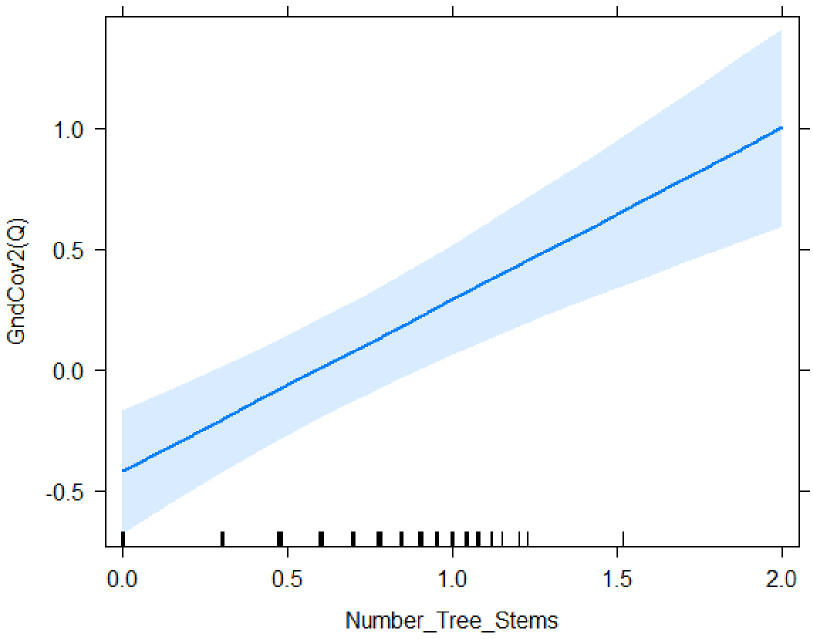


Figure A4.7: Effects plot for the alternate GLM for GndCov2(Q) showing the number of tree stems on a quadrat as the best predictor. Explanations of the principal components are in Table 5.3

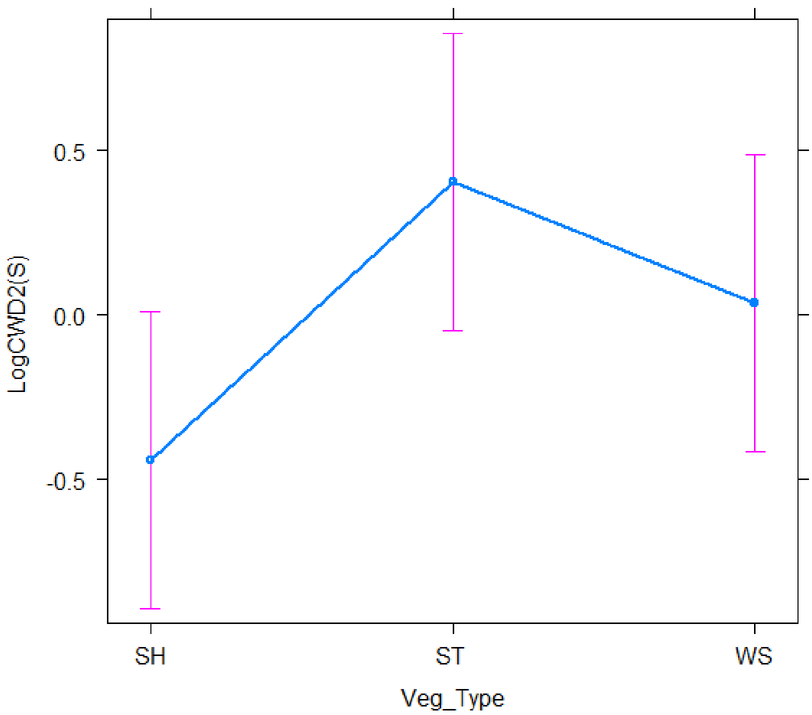


Figure A4.8: Effects plot for the best GLM for LogCWD2(S) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

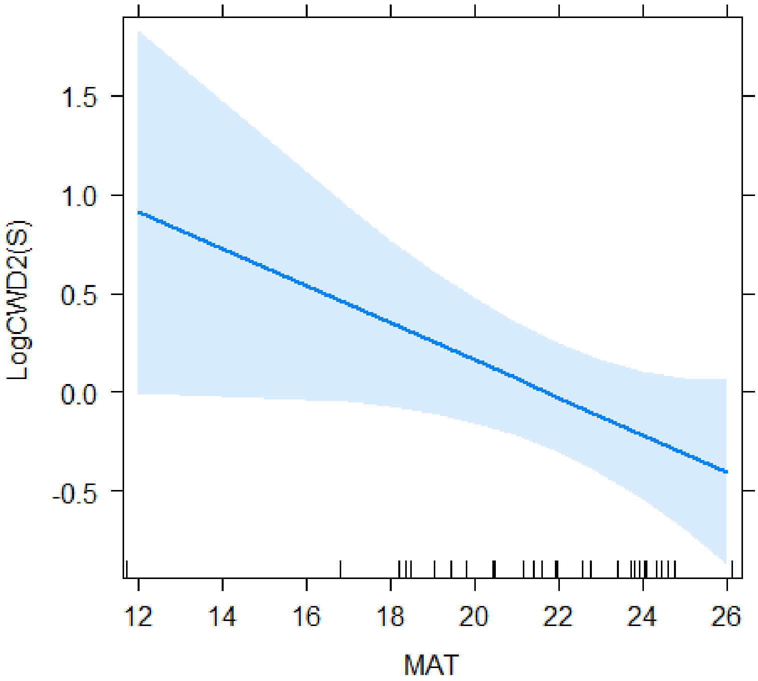


Figure A4.9: Effects plot for the alternate GLM for LogCWD2(S) showing mean annual temperature (MAT, ºC) as the best predictor. Explanations of the principal components are in Table 5.3

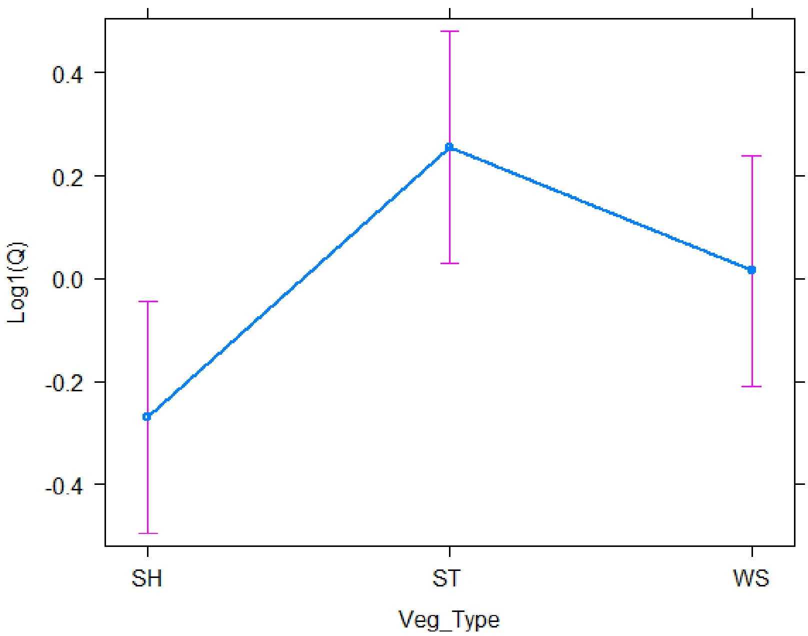


Figure A4.10: Effects plot for the best GLM for LogCWD2(S) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

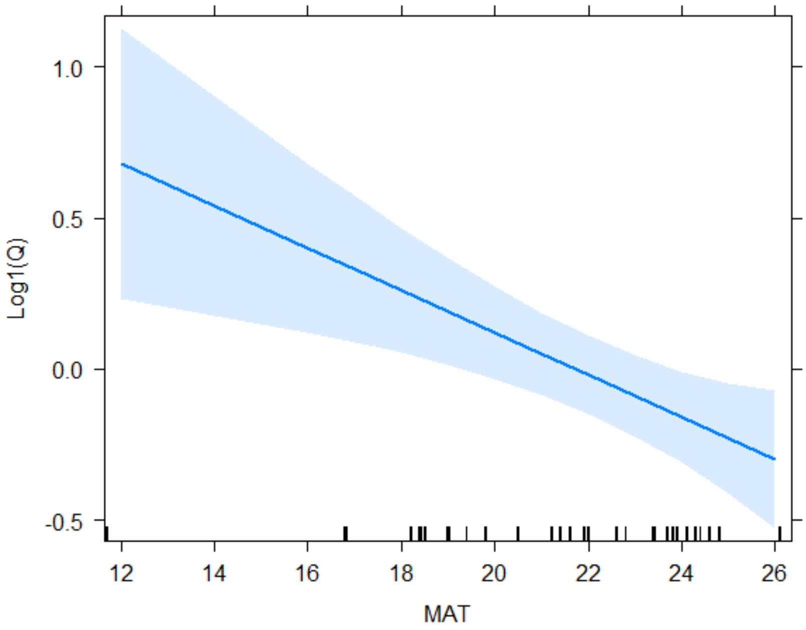


Figure A4.11: Effects plot for the alternate GLM for LogCWD2(S) showing mean annual temperature (MAT, °C) as the best predictor. Explanations of the principal components are in Table 5.3

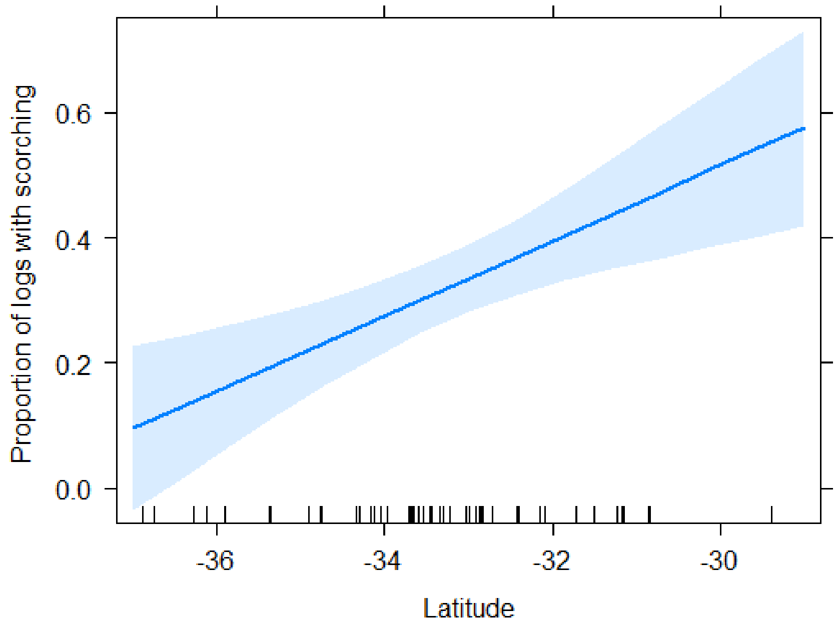


Figure A4.12: Effects plot for the best GLM for the proportion of logs on a site with scorching showing latitude as the best predictor. Explanations of the habitat variables are in Table 2.9

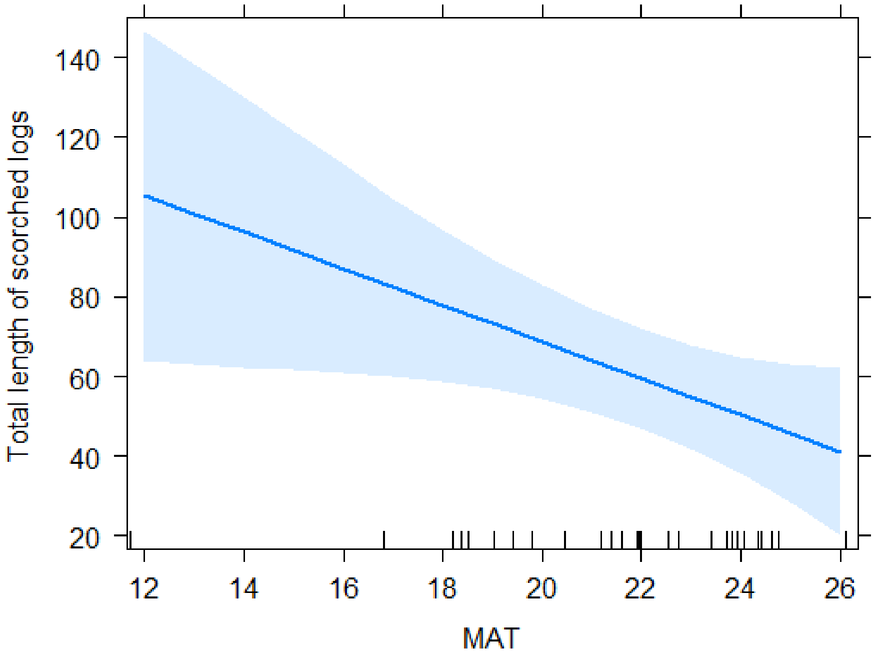


Figure A4.13: Effects plot for the best GLM for the total length of scorched logs on a site showing mean annual temperature (MAT, ^{o}C) as the best predictor. Explanations of the habitat variables are in Table 2.9

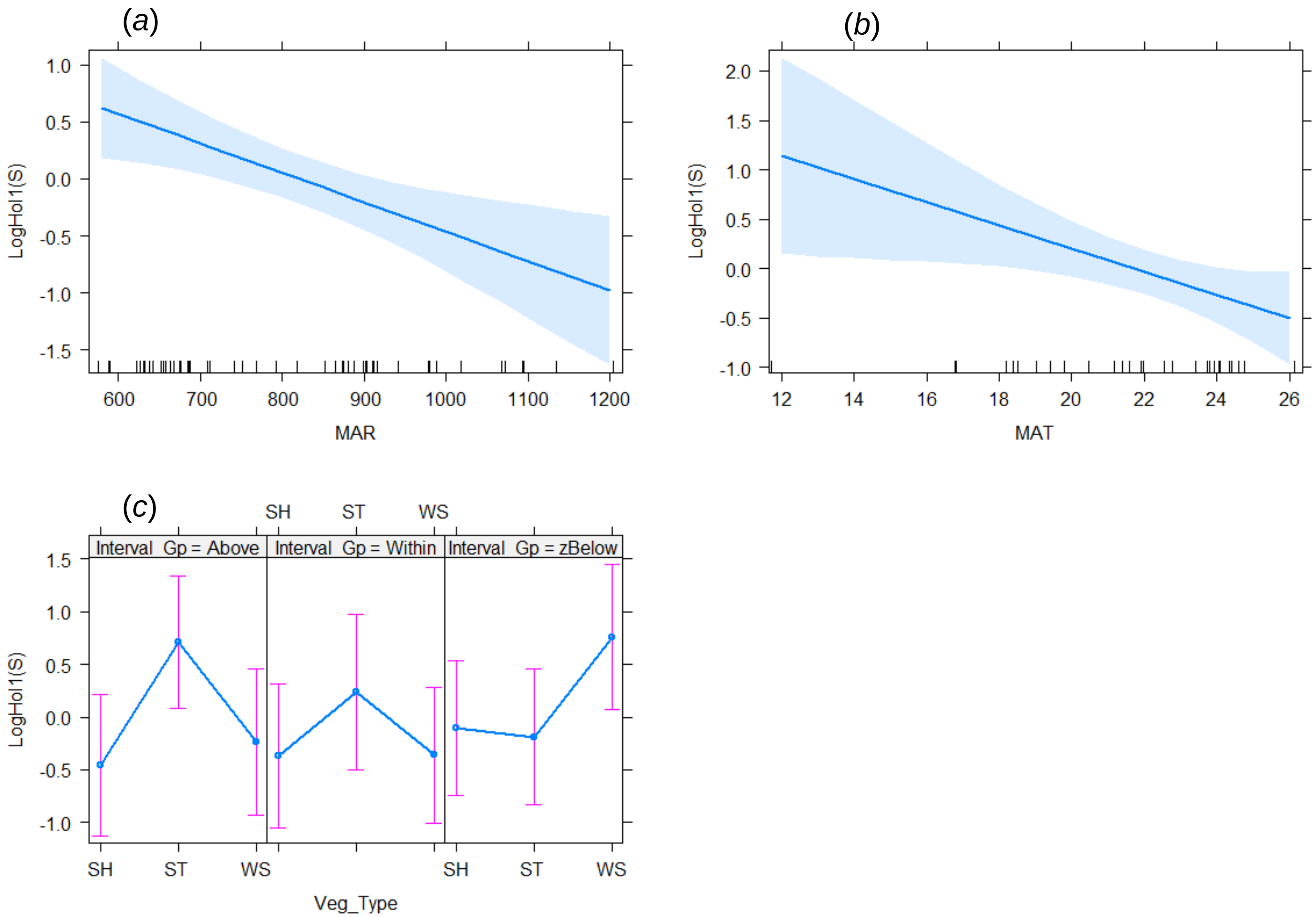


Figure A4.14: Effects plot for the best GLM for LogHol1(S): (*a*) mean annual rainfall (MAR, mm); (*b*) mean annual temperature (MAR, ^{o}C); and (*c*) vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) interacting with interval group (interval (below) = below minimum recommended intervals; interval (within) = within recommended intervals; interval (above) = above recommended intervals). Explanations of the principal components are in Table 5.3

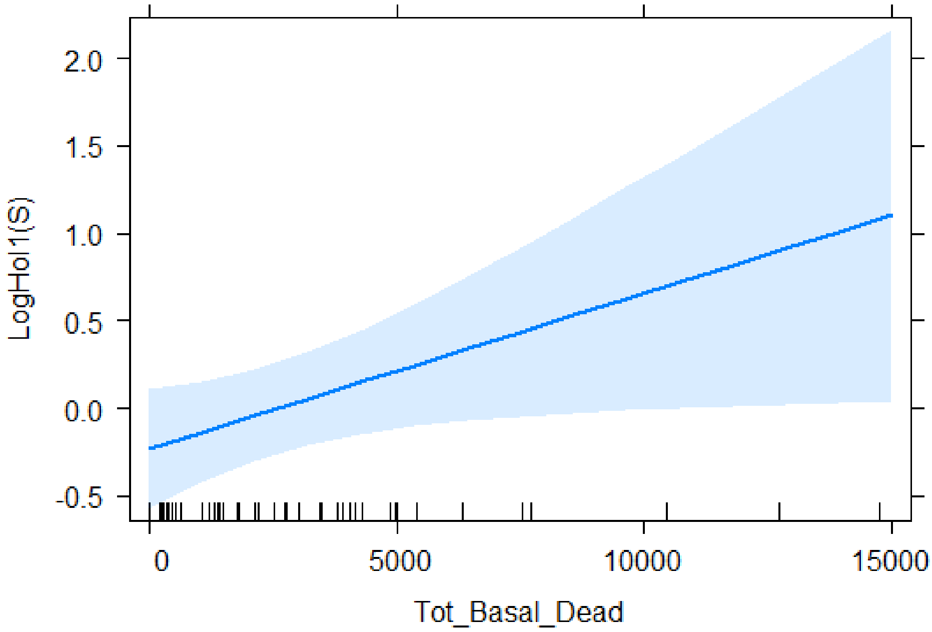


Figure A4.15: Effects plot for the alternate GLM for LogHol1(S) showing the total basal area (cm^3) of dead trees on a site as the best predictor. Explanations of the principal components are in Table 5.3

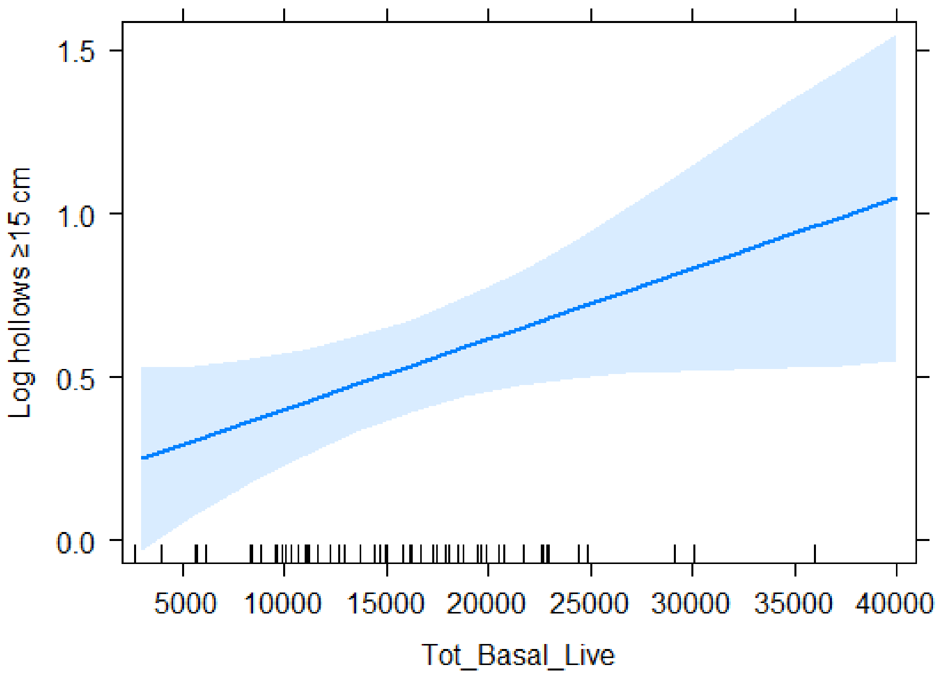


Figure A4.16: Effects plot for the best GLM for the presence of large log hollows (≥15 cm) showing the total basal area (cm^3) of live trees on a site as the best predictor. Explanations of the habitat variables are in Table 2.9

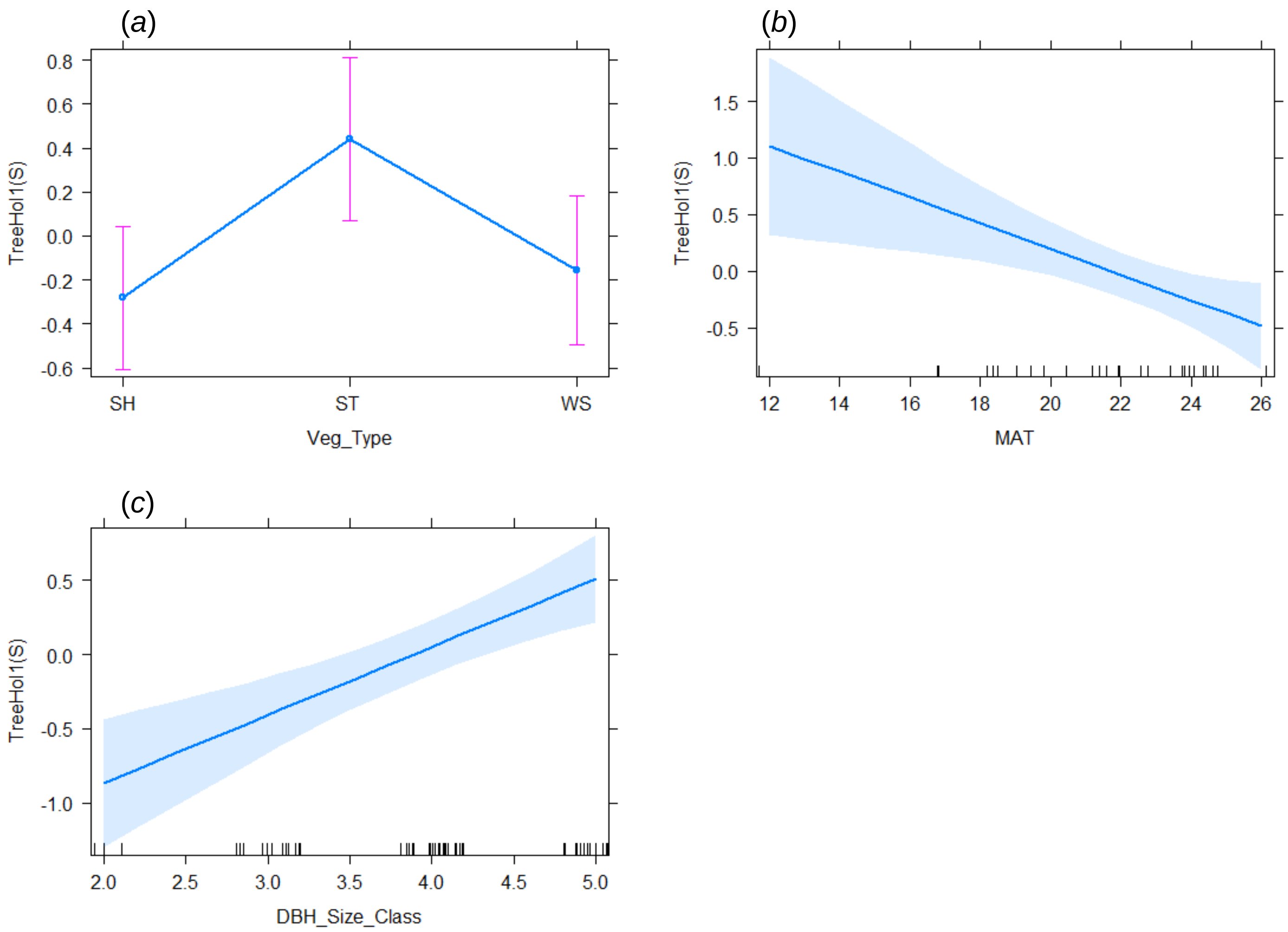


Figure A4.17: Effects plot for the best GLM for TreeHol1(S): (*a*) vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes); (*b*) mean annual temperature (MAR, °C); and (*c*) the number of different DBH size classes on a site. Explanations of the principal components are in Table 5.3

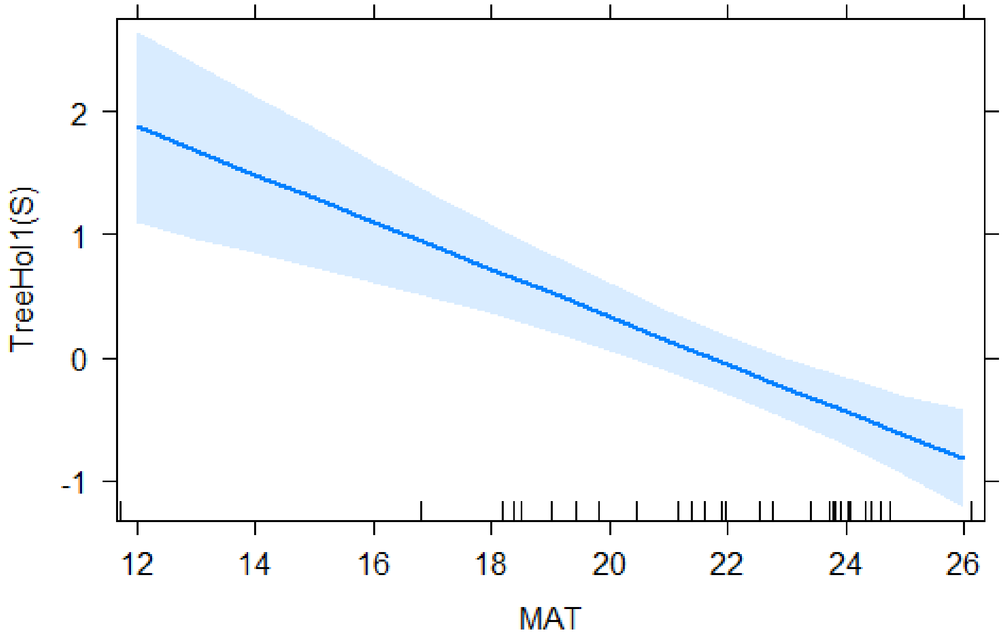


Figure A4.18: Effects plot for the alternate GLM for TreeHol1(S) showing mean annual temperature (MAR, ºC) as the best predictor. Explanations of the principal components are in Table 5.3

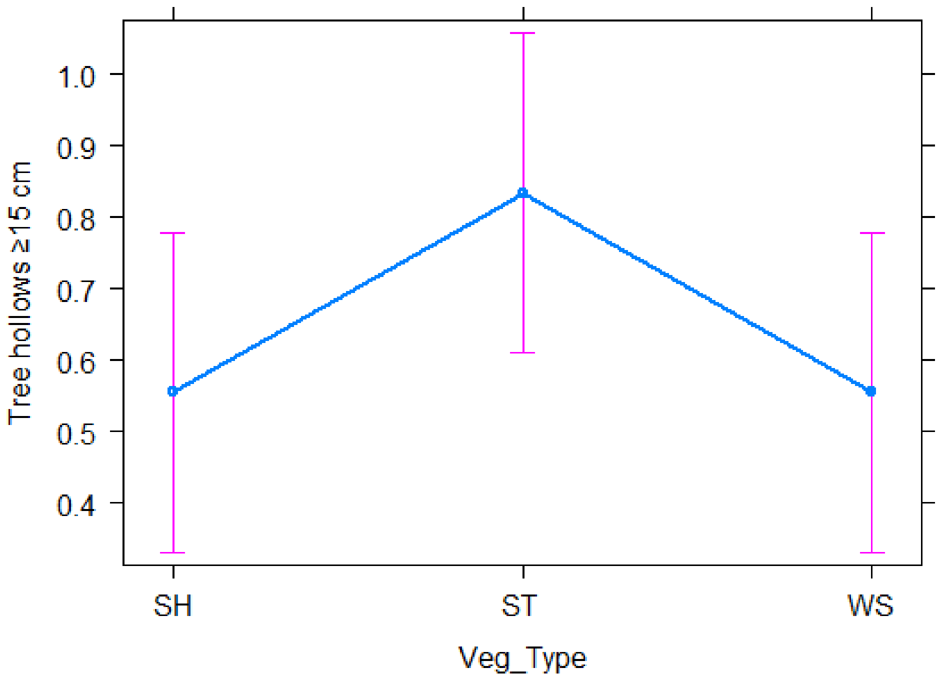


Figure A4.19: Effects plot for the best GLM for the presence of large tree hollows (≥15 cm) on a site showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the habitat variables are in Table 2.9

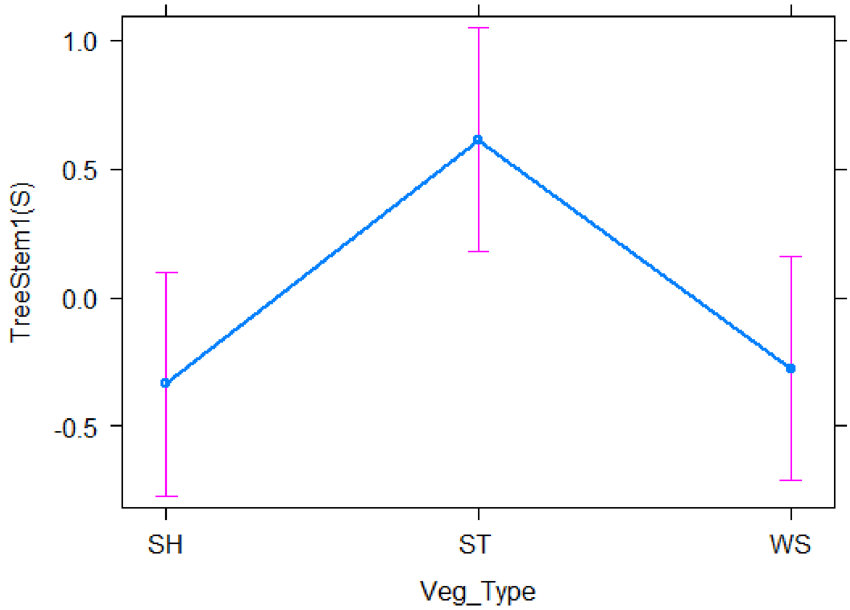


Figure A4.20: Effects plot for the best GLM for TreeStem1(S) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

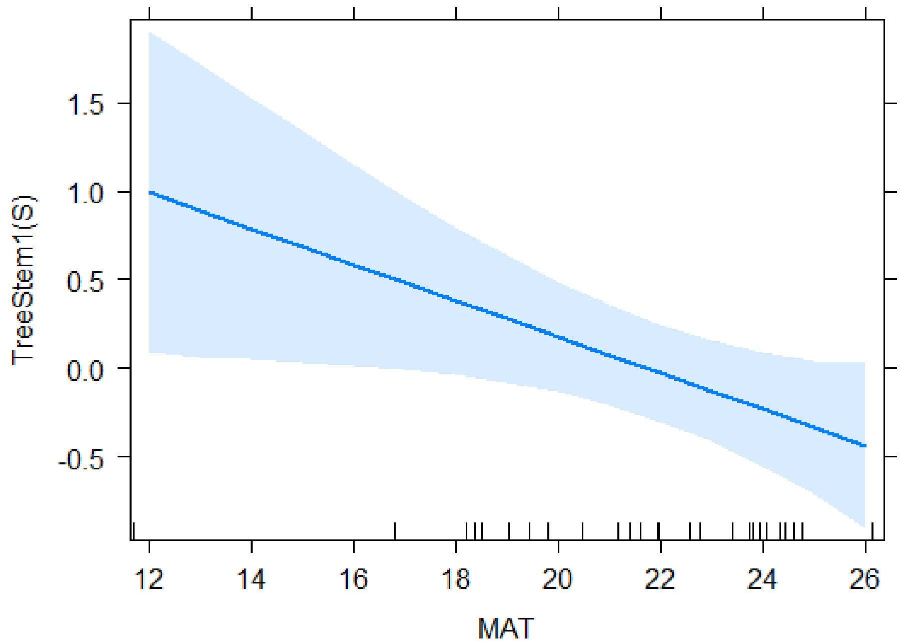


Figure A4.21: Effects plot for the alternate GLM for TreeStem1(S) showing mean annual temperature (MAT, ^{o}C) as the best predictor. Explanations of the principal components are in Table 5.3

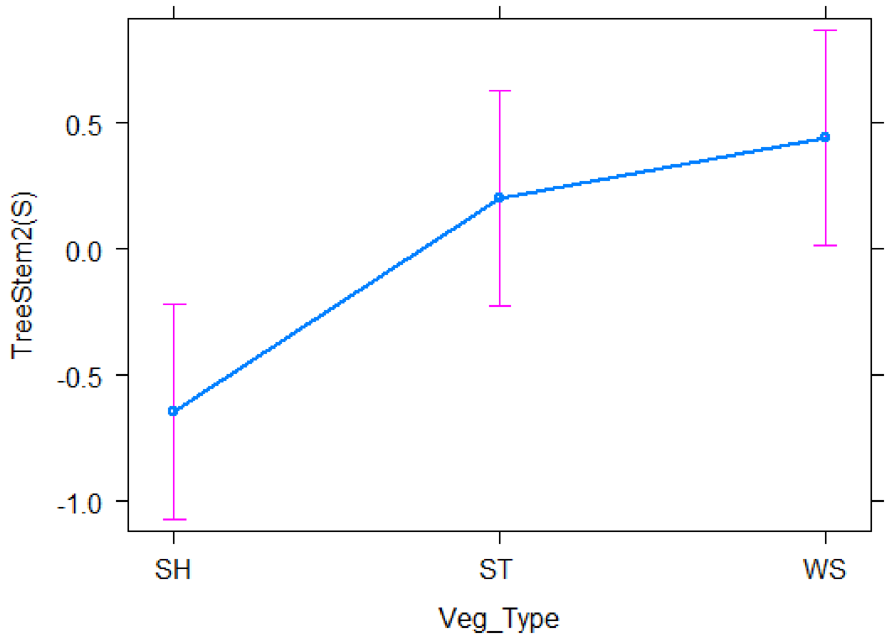


Figure A4.22: Effects plot for the best GLM for TreeStem2(S) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

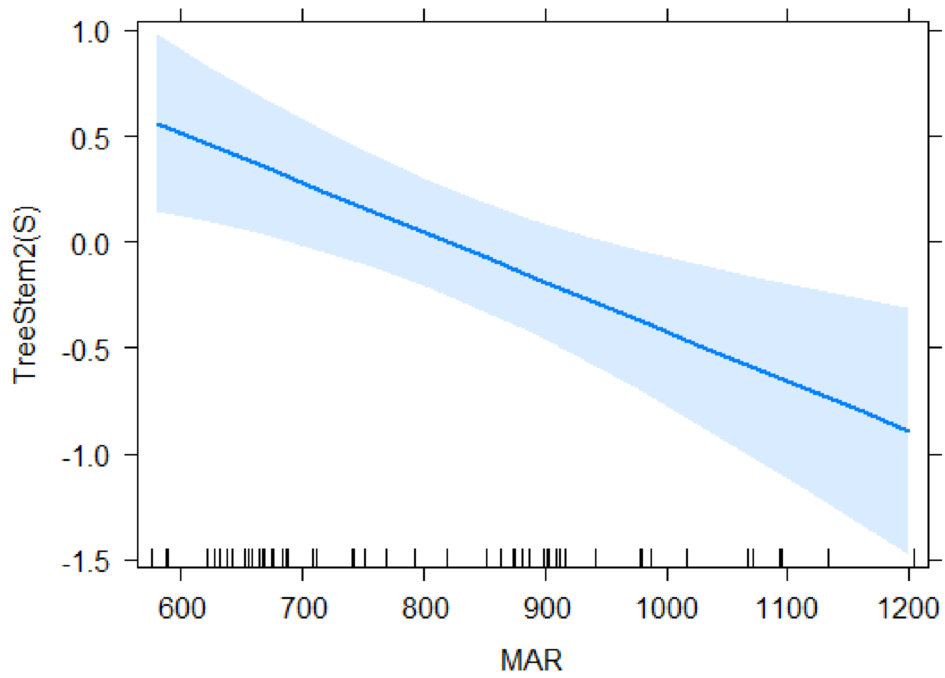


Figure A4.23: Effects plot for the alternate GLM for TreeStem2(S) showing mean annual rainfall (MAR, mm) as the best predictor. Explanations of the principal components are in Table 5.3

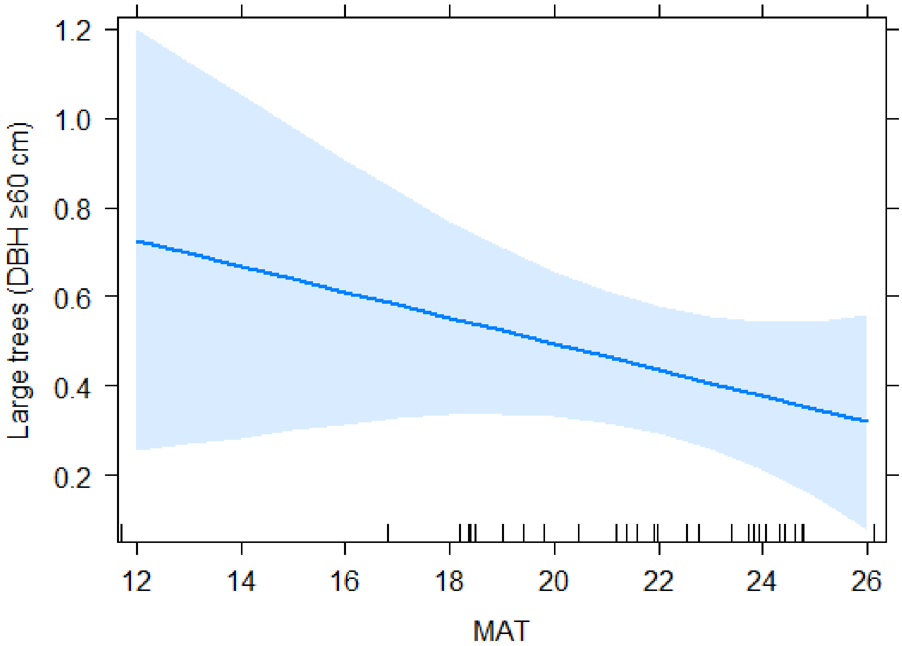


Figure A4.24: Effects plot for the best GLM for the presence of large trees (DBH ≥60 cm) on a site showing mean annual temperature (MAT, ºC) as the best predictor. Explanations of the habitat variables are in Table 2.9

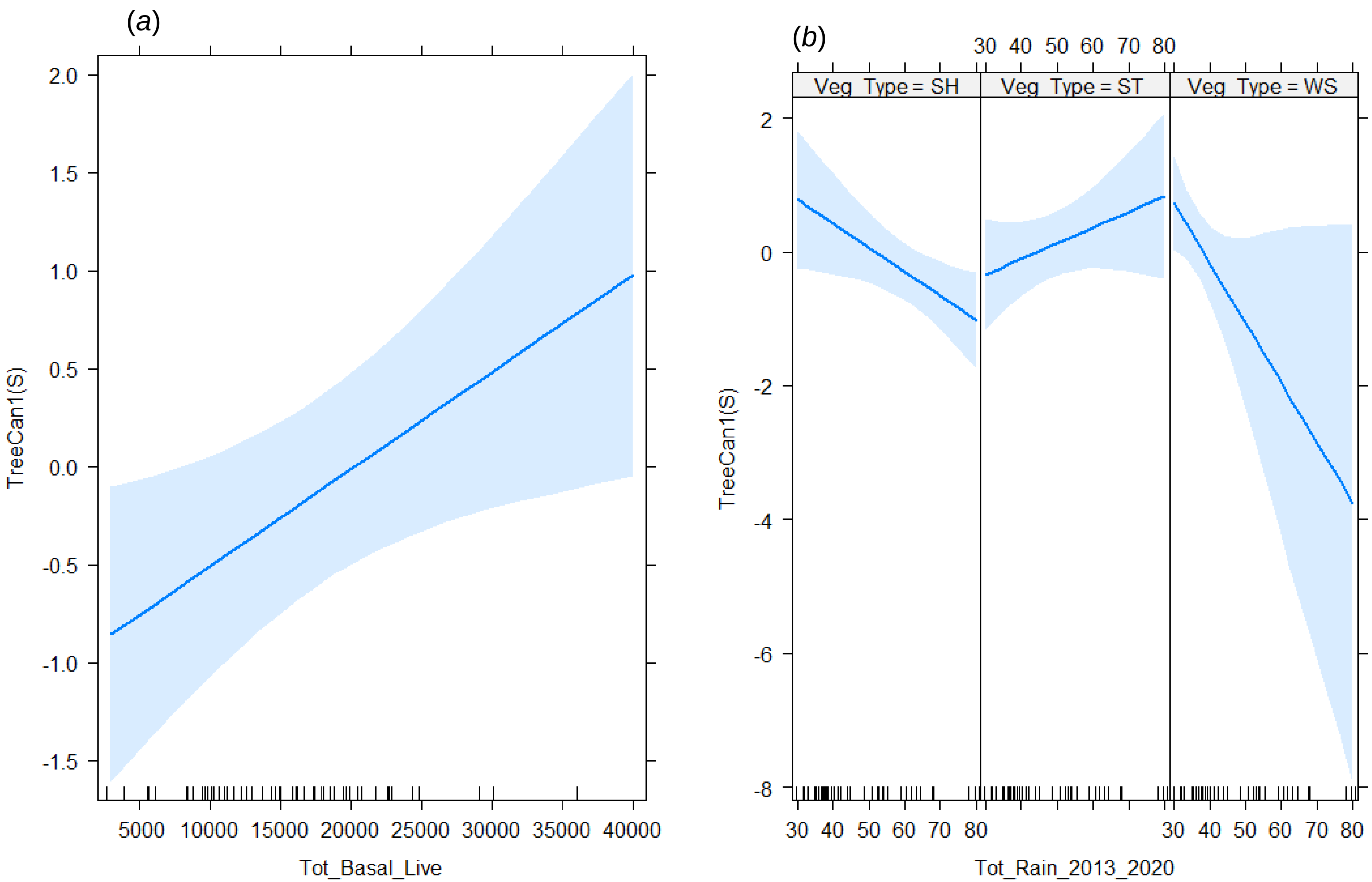


Figure A4.25: Effects plot for the best GLM for TreeCan1(S): (*a*) total basal area (cm^3) of live trees on a site; and (*b*) vegetation type (SH = Southern Tablelands, ST = Sydney Hinterlands, WS = Western Slopes) interacting with the total rainfall recorded between 2013 and 2020 (cm). Explanations of the principal components are in Table 5.3

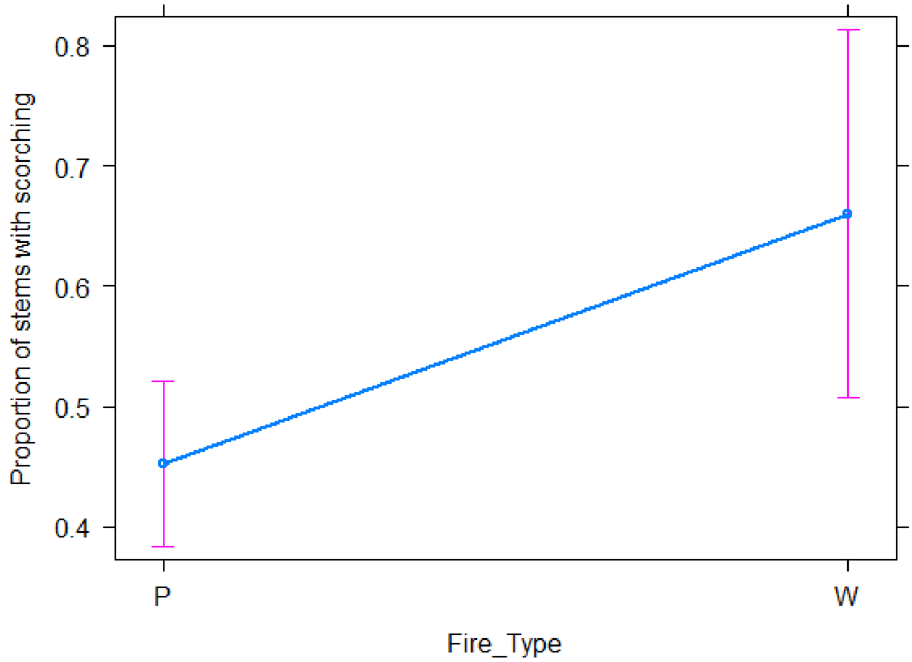


Figure A4.26: Effects plot for the best GLM for the proportion of stems with scorching on a site showing fire type (p = prescribed, w = wild) as the best predictor. Explanations of the habitat variables are in Table 2.9

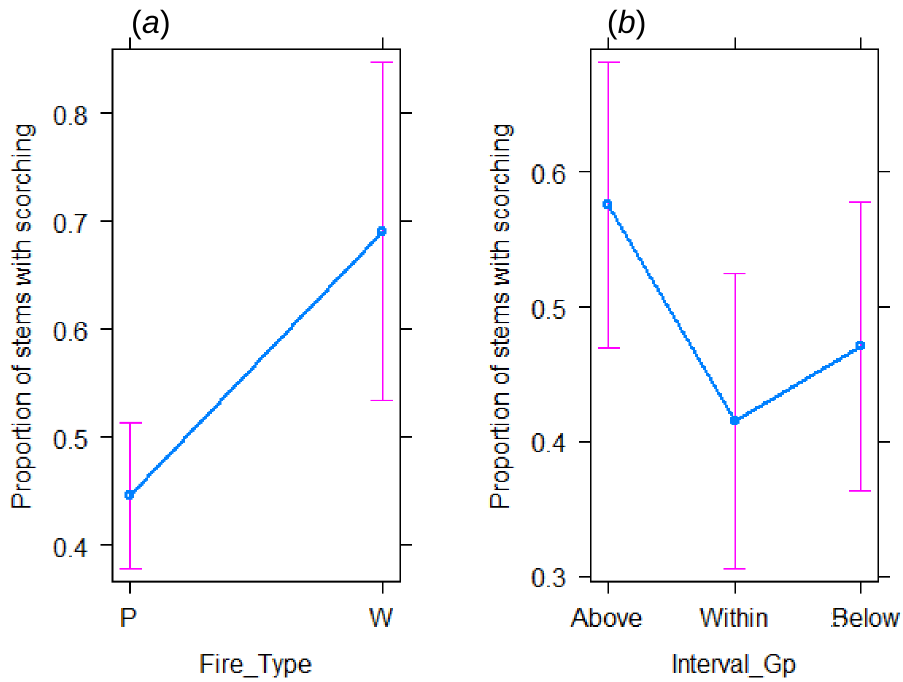


Figure A4.27: Effects plot for the alternate GLM for the proportion of stems with scorching: (*a*) fire type (p = prescribed, w = wild); and (*b*) interval group (interval (below) = below minimum recommended intervals; interval (within) = within recommended intervals; interval (above) = above recommended intervals). Explanations of the habitat variables are in Table 2.9

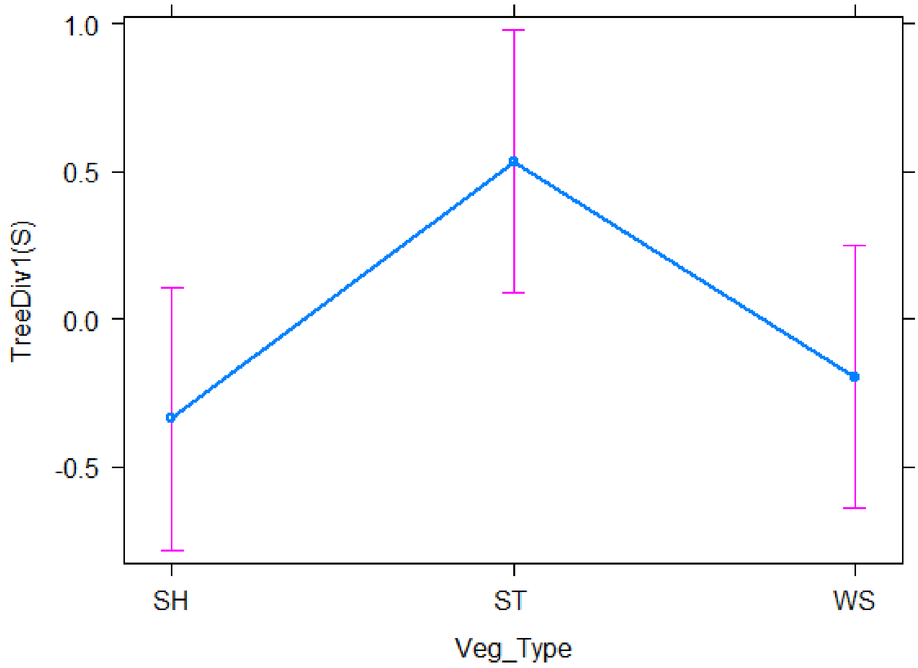


Figure A4.28: Effects plot for the best GLM for TreeDiv1(S) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

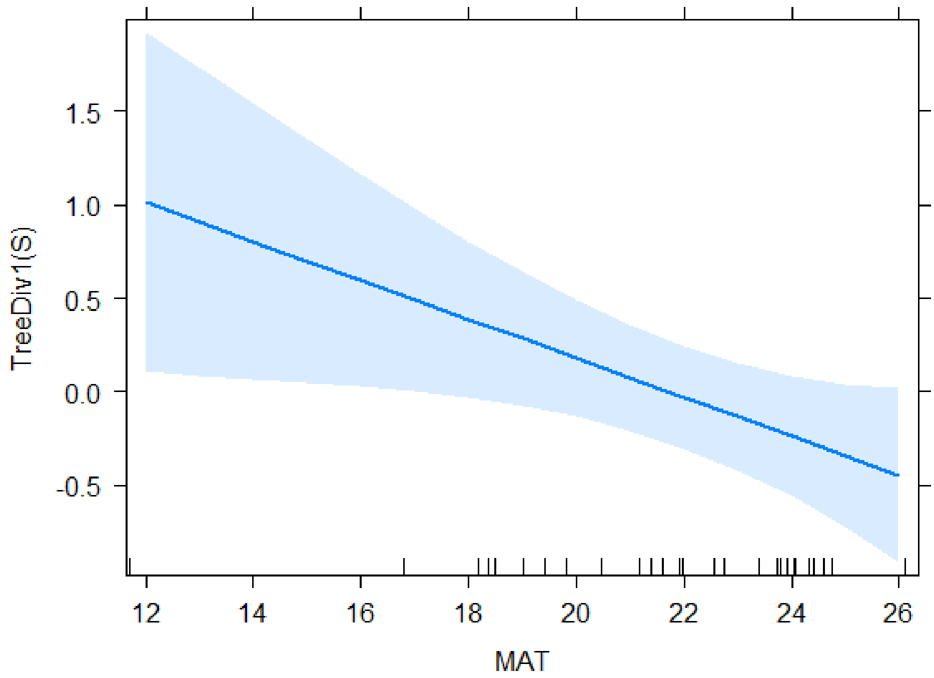


Figure A4.29: Effects plot for the alternate GLM for TreeDiv1(S) showing mean annual temperature (MAT, °C) as the best predictor. Explanations of the principal components are in Table 5.3

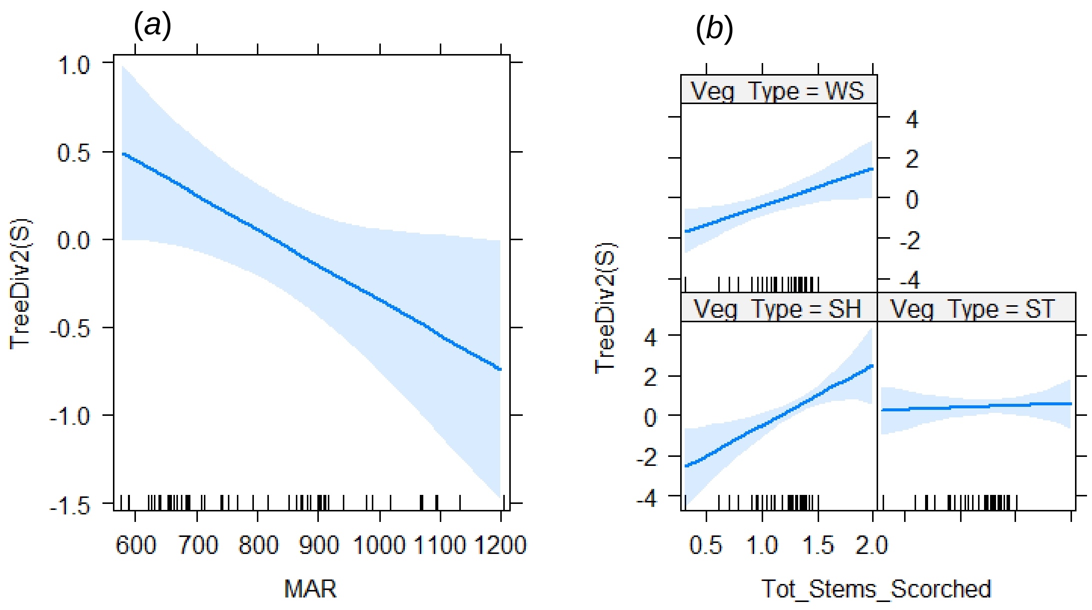


Figure A4.30: Effects plot for the best GLM for TreeDiv2(S): (*a*) mean annual temperature (MAT, °C); and (*b*) vegetation type (SH = Southern Tablelands, ST = Sydney Hinterlands, WS = Western Slopes) interacting with the total number of scorched stems on a site. Explanations of the principal components are in Table 5.3

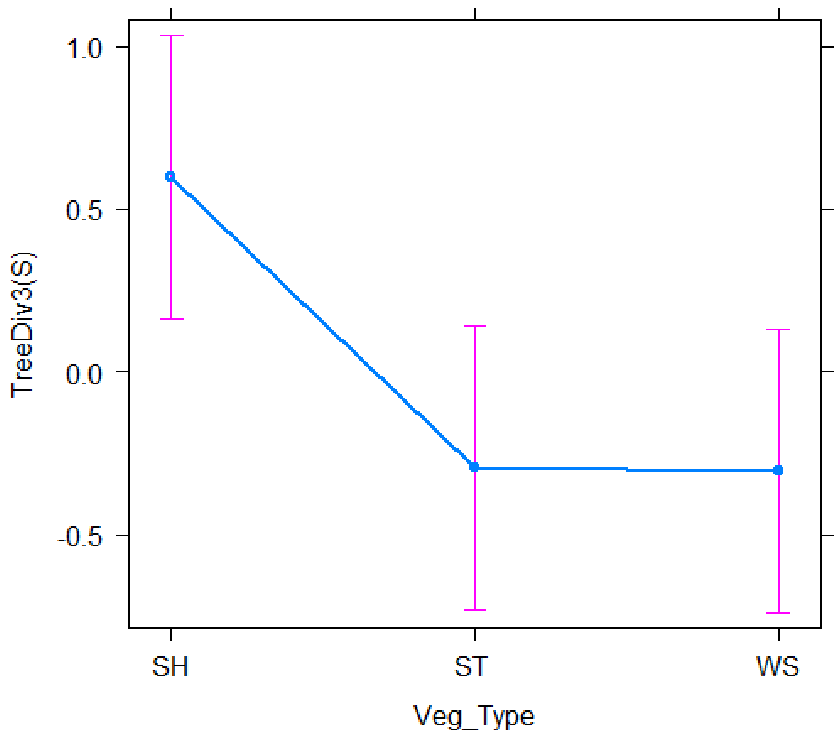


Figure A4.31: Effects plot for the best GLM for TreeDiv3(S) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

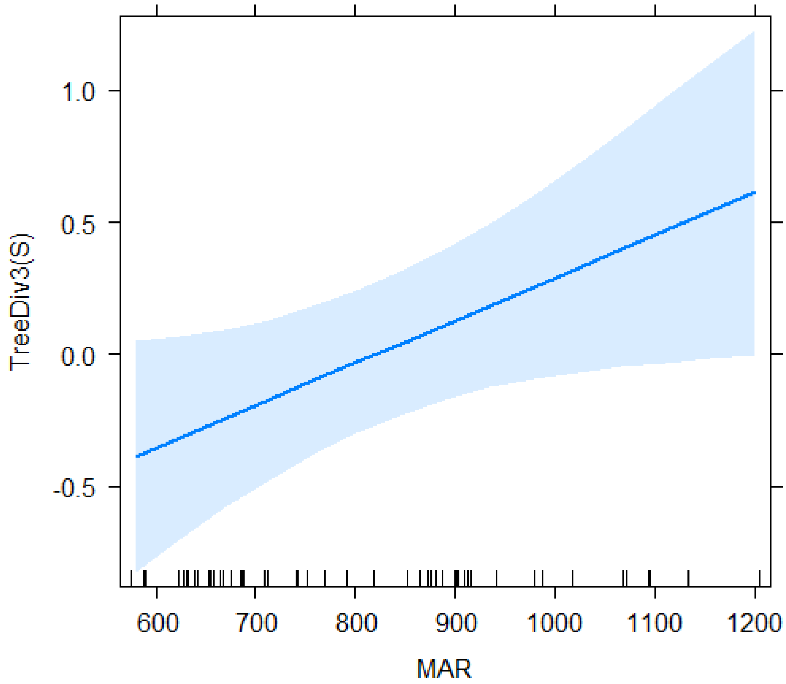


Figure A4.32: Effects plot for the alternate GLM for TreeDiv3(S) showing mean annual rainfall (MAR, mm) as the best predictor. Explanations of the principal components are in Table 5.3

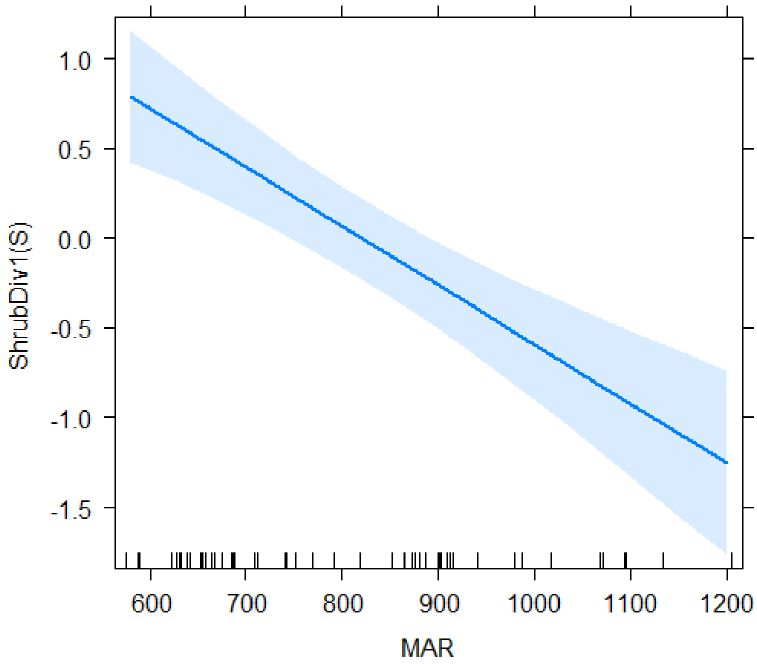


Figure A4.33: Effects plot for the best GLM for ShrubDiv1(S) showing mean annual rainfall (MAR, mm) as the best predictor. Explanations of the principal components are in Table 5.3

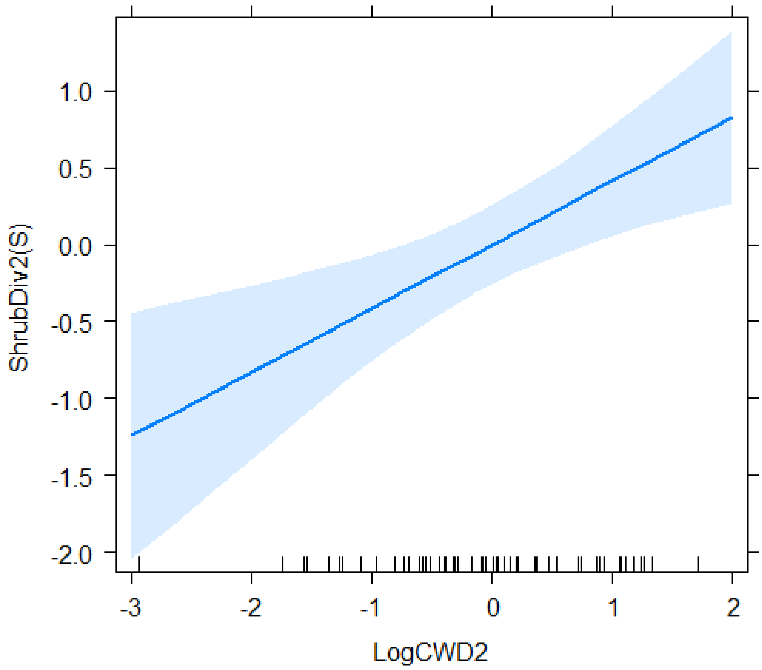


Figure A4.34: Effects plot for the best GLM for ShrubDiv2(S) showing LogCWD2 as the best predictor. Explanations of the principal components are in Table 5.3

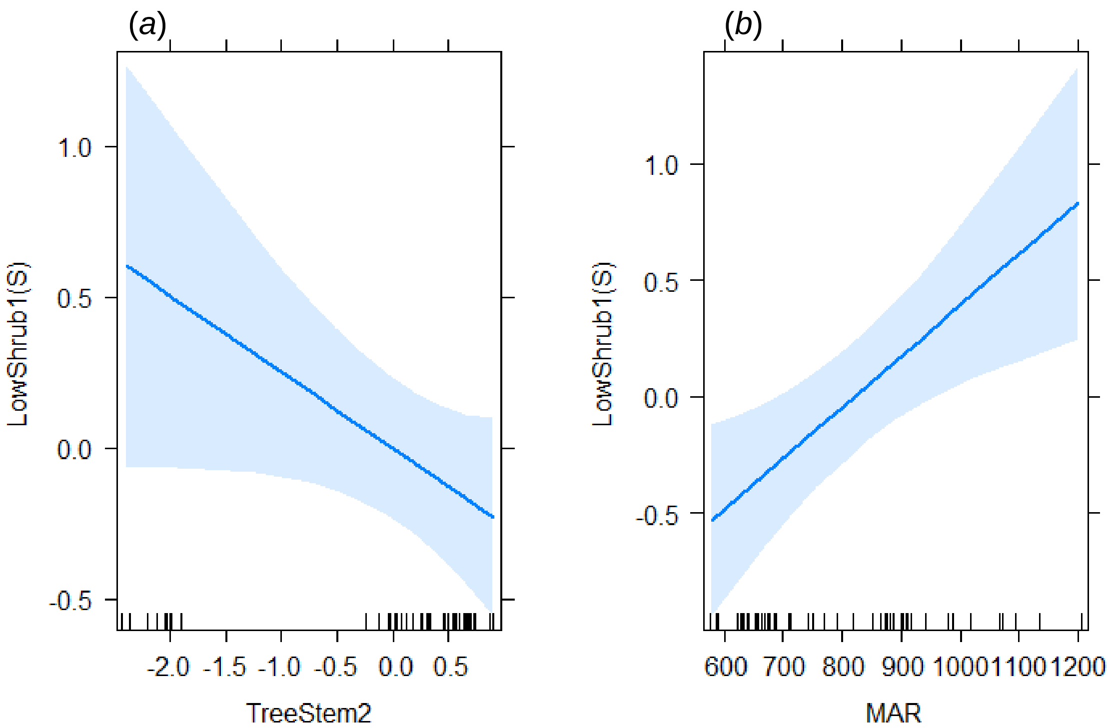


Figure A4.35: Effects plot for the best GLM for LowShrub1(S): (*a*) TreeStem2; and (*b*) mean annual rainfall (MAR, mm). Explanations of the principal components are in Table 5.3

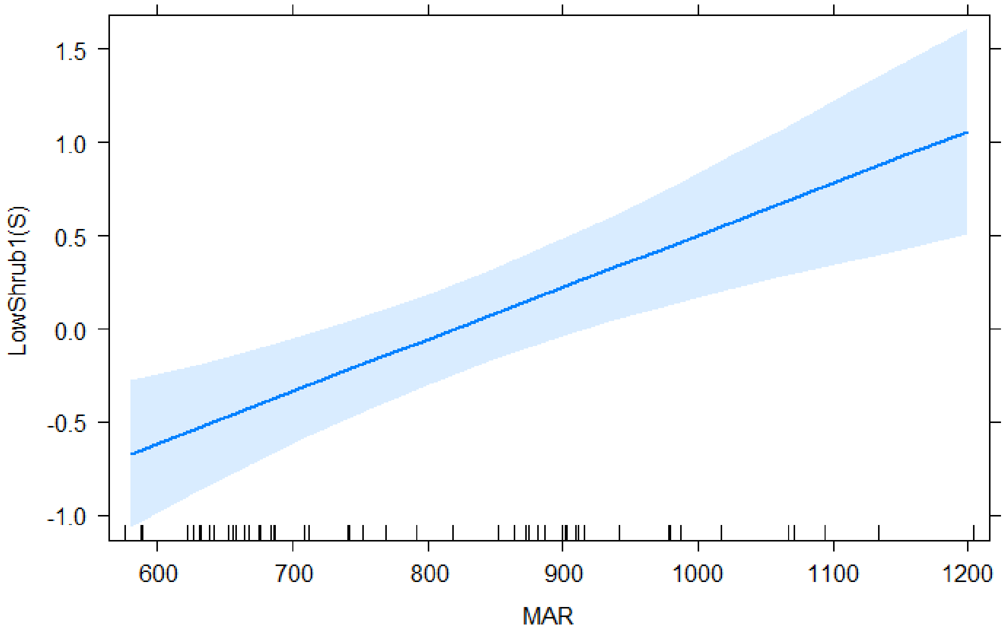


Figure A4.36: Effects plot for the alternate GLM for LowShrub1(S) showing mean annual rainfall (MAR, mm) as the best predictor. Explanations of the principal components are in Table 5.3

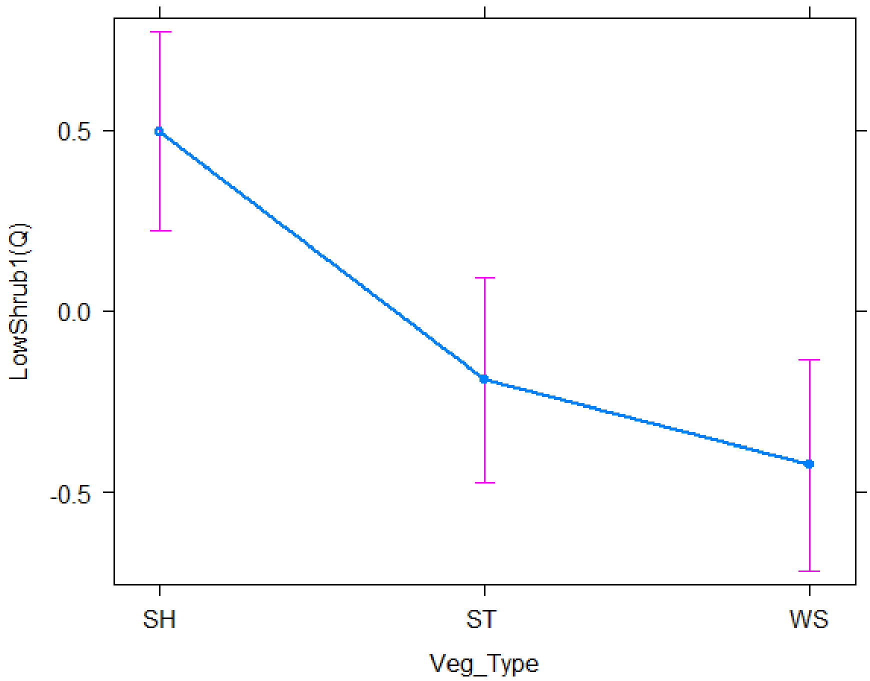


Figure A4.37: Effects plot for the best GLM for LowShrub1(Q) showing vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes) as the best predictor. Explanations of the principal components are in Table 5.3

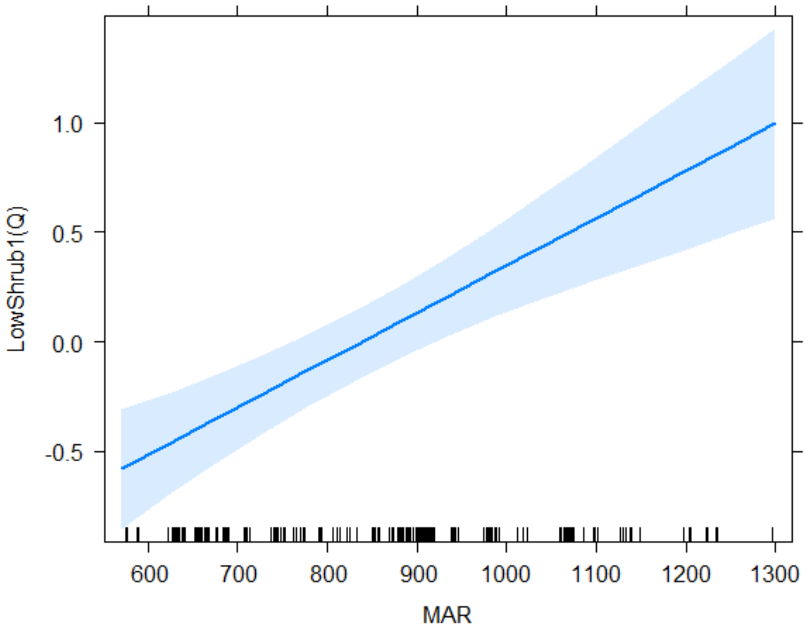


Figure A4.38: Effects plot for the alternate GLM for LowShrub1(Q) showing mean annual rainfall (MAR, mm) as the best predictor. Explanations of the principal components are in Table 5.3

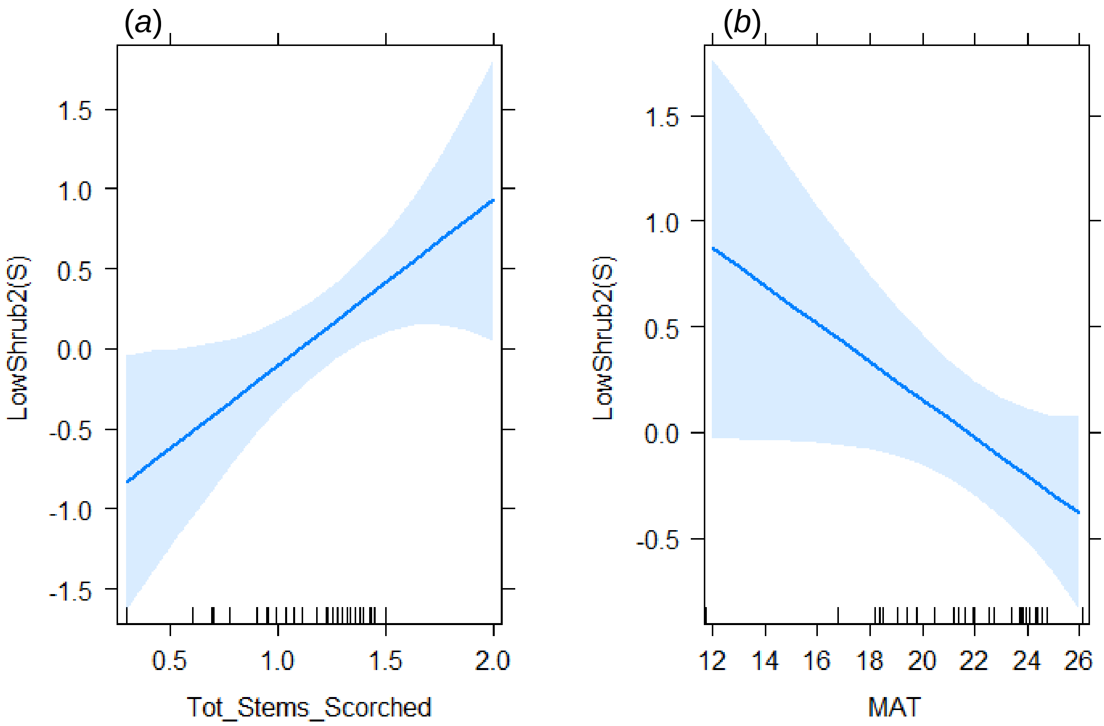


Figure A4.39: Effects plot for the best GLM for LowShrub1(S): (*a*) the total number of scorched stems on a site; and (*b*) mean annual temperature (MAT, °C). Explanations of the principal components are in Table 5.3

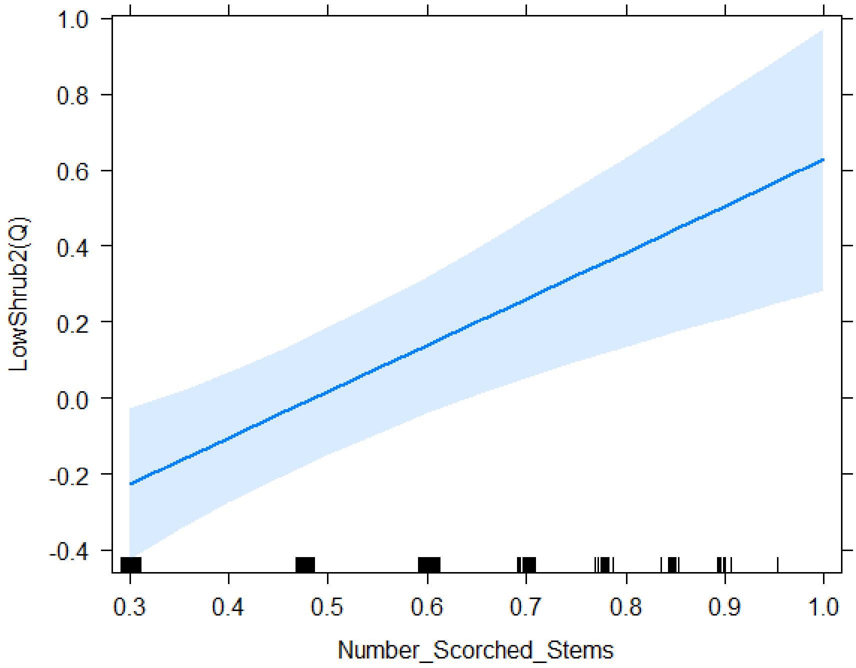


Figure A4.40: Effects plot for the best GLM for LowShrub2(Q) showing the number of scorched stems on a quadrat as the best predictor. Explanations of the principal components are in Table 5.3

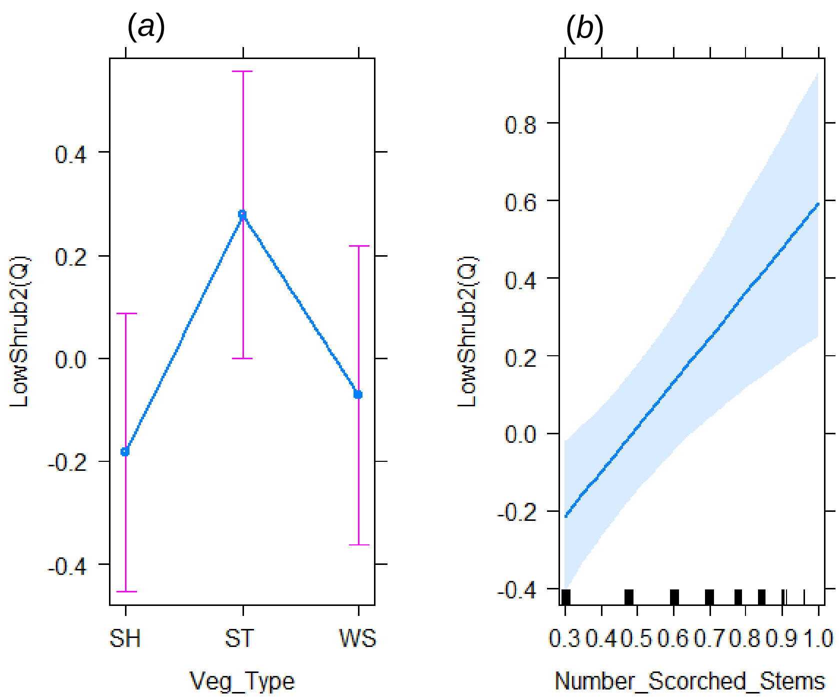


Figure A4.41: Effects plot for the alternate GLM for LowShrub2(Q): (*a*) vegetation type (mean ± SE; SH = Sydney Hinterlands, ST = Southern Tablelands, WS = Western Slopes); and (*b*) the number of scorched stems on a quadrat. Explanations of the principal components are in Table 5.3

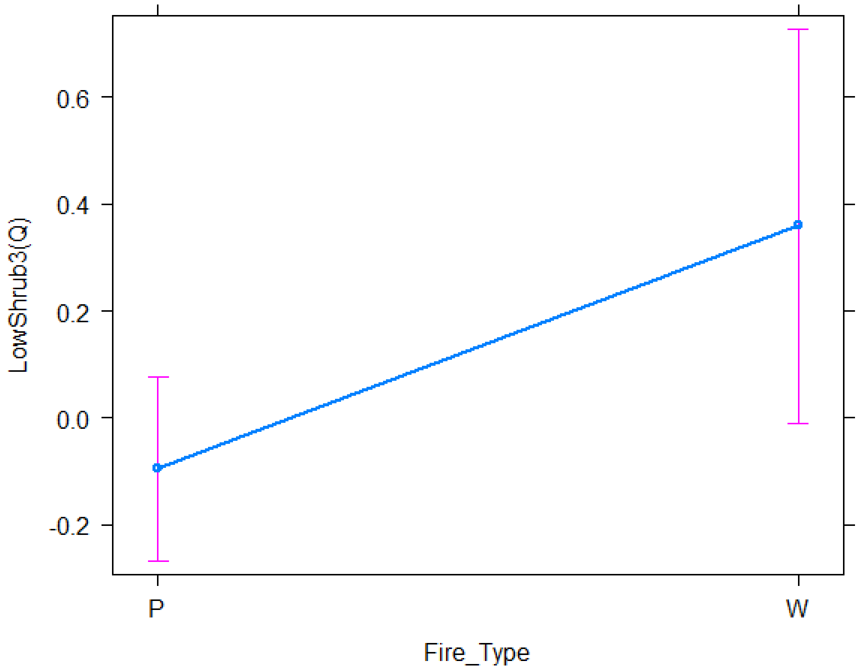


Figure A4.42: Effects plot for the best GLM for LowShrub3(Q) showing fire type (p = prescribed, w = wild) as the best predictor. Explanations of the principal components are in Table 5.3