2018

Within-fire patchiness associated with prescribed burning in the northern Jarrah forests of Western Australia

Zigourney Nielsen
Edith Cowan University

Within-fire patchiness associated with prescribed burning in the northern Jarrah forests of Western Australia

Master of Science (Environmental Management)

Zigourney Nielsen

2018

Supervisors: Professor William D. Stock, Dr Eddie Van Etten

Centre for Ecosystem Management, School of Science, Edith Cowan University, Joondalup Western Australia

Abstract

There is growing understanding of the importance of landscape mosaics and heterogeneity for biodiversity outcomes in Western Australia. However, there is limited information on the patchiness (spatial configuration of unburnt and burnt patches which occur at a range of spatial scales) within the perimeter of a single prescribed burn. Of particular concern is the idea that prescribed burning operations, carried out under very restricted weather and environmental conditions, can lead to structural and floristic homogenization of the area within a burn perimeter. This may be evident as reduced post-fire vegetation patchiness.

Western Australian Jarrah (*Eucalyptus marginata*) forests are managed to reduce fuel loads to protect life and property. Additionally, specific biodiversity and fuel reduction programs are completed by means of low intensity controlled burns carried out by the Parks and Wildlife Service, part of the Department of Biodiversity, Conservation and Attractions. The northern Jarrah forest is thus an ideal study site to test whether prescribed burning homogenizes a within-burn area. The objective of this study was to determine the post-fire patchiness of vegetation following prescribed burning to assess the potential for homogenisation of the within-burn area of Jarrah forests. To achieve this, a set of post-burn surveys were created to determine the patchiness of the burnt areas within 18 prescribed burns. The quantitative post-burn assessment designed in this study was evaluated to determine if it is suitable to be used as a possible future management option.

A survey was undertaken to obtain data on 29 environmental variables which capture the variability across an individual prescribed burn area to determine the within-burn fire characteristics. A Pearson correlation matrix table was constructed to determine the significant correlations between variables as well as the strength of the relationships (coefficient of determination, r^2). The patchiness between seasons autumn and spring was compared. Generalised Linear Modelling (GLM), and the application of Akaike were used to identify which variables were essential and most significant in predicting patchiness, to produce a list of candidate models. The AICc indicated which models were the most parsimonious or plausible candidate models (AICc < 2). Structured Equation Modelling (SEM) was completed to determine which variables in the 'most parsimonious' model were the greatest contributors to the model.

It was found that the number of vegetation patches decreased with an increase in fire intensity and percentage of area burnt. Autumn and spring burns were not significantly different in terms of overall patchiness and the majority of patches were found to be small, between 1 – 10 m in length. Surface Moisture Content (SMC) was the only pre-fire condition variable that negatively influenced prescribed burn fire intensity and subsequently patchiness, while time since last burn was found to increase the number of vegetation patches and SMC. The post-fire survey data obtained in this study on the 18 post fire sites was also compared to the post-burn assessments completed by Parks and Wildlife Service on the same sites.

GLM and AICc showed that the variables Fire Danger Index, ash cover (%), area burnt (%), month of fire and the number of vegetation patches, are the most parsimonious and 'best' fit at predictors of patchiness within a prescribed burn area. While SEM showed that area burnt (%) was the most important predictor of patchiness. Within-burn patchiness appeared to be low in the study sites. Results from the prescribed burns in the northern jarrah forests showed that in most prescribed fires, 90 to 100% of the vegetation area was burnt with a limited number of unburned patches (up to 12 km^{-1}) remaining. Although successful for fuel reduction burning, such large scale vegetation loss has been found to lead to structural homogenisation within a burn area, which in turn can result in long-term impacts on biodiversity. This study thus showed that prescribed burns in the northern Jarrah forest can homogenise the within-burn area and the implications of these findings are discussed in the broader context of landscape patchiness. This study also shows that a quantitative post-fire patchiness survey similar to that designed here should be developed as a future management option.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(ii) contain any material previously published or written by another person except where due reference is made in the text; or

(iii) contain any defamatory material.

I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis as required.

[redacted]

Zigourney Nielsen

06/04/2018

Use of Thesis

Acknowledgements

There were definitely some ups and downs over the past three and a half years of part-time study however it is safe to say that this thesis was a life changer. I have learnt and experienced a lot and have met some truly amazing people along the way, to whom I would not have been able to complete my thesis without. Firstly, I would like to give a massive thank you to my supervisors Professor William Stock and Dr Eddie Van Etten for their guidance, commitment and extreme knowledge. To Will specifically, thank you for your time, patience and keeping me on track! I could not have asked for better supervisors. I would like to thank and extend my gratitude to Mr Michael Pasotti, Parks and Wildlife Service District Fire Coordinator, Perth Hills District, whom assisted me with hours of field work preparation. Michael's assistance in this project is invaluable and I appreciate the time he gave out of his busy schedule to answer any question I had.

I would also like to extend my appreciation and thanks to everyone who helped me in the field, including Maryann White, Aaron Daff, Candice Le Roux and Steven Spragg, I do not know what I would have done without you! Thank you for your company, help and enthusiasm, we definitely needed that last one when walking through thick *Banksia sessilis*! And to all my friends that I have met along this journey, thank you all. I know I didn't come in to the office much but when I did it felt like I never left. You were always so welcoming and made my university days that much more enjoyable, thank you again, you know who you are!

I would also like to thank my parents Mandy and Soren Nielsen and my brothers for their patience and understanding when I was stressed and for their encouraging words right until the end. Finally, for his encouragement and patience, I would like to thank my partner Matthew Keeble, for helping me in the field and pushing me until completion. Thank you again to everyone, I could not have completed this degree without you all.

Table of Contents

Abstract iii

Declaration v

Use of Thesis vi

Acknowledgements vii

Introduction 1

1.1. History of fire 1

1.1.1. The first fire 1

1.1.2. Prescribed burning and mechanical treatment 2

1.1.3. South-west Western Australia forest biodiversity 3

1.1.4. Forest heterogeneity 4

1.1.5. Pyrodiversity in forest systems 5

1.2. Fire characteristics 6

1.3. Fire behaviour 7

1.4. Fuel 8

1.5. Jarrah forest structure and characteristics 9

1.6. Patchiness within a single burn 11

1.7. Prescribed burns and current post-burn assessments 12

1.7.1. Parks and Wildlife Service prescribed fire protocols 12

1.7.2. Prescribed burn planning process 12

1.7.3. Prescribed burn categories 13

1.7.4. Prescribed Fire Plan – Success criteria and Objectives 13

1.7.5. Post burn assessment 13

Objectives 17

Methods 18

2.1 Selection of Study Sites 18

2.2 Development of survey and field monitoring sheets 22

2.2.1 Survey Templates 22

2.2.2 Data collection 25

2.2.3 Data collection techniques and variables collected 25

2.3 Data analysis to determine patchiness creating variables 31

2.3.1 Pearson correlation analysis – Matrix table 31

2.3.2 Season of burn 31

2.3.3 Time since last burn, # veg patches and fire intensity 32

2.3.4 Elimination of covaring variables 32

2.3.5 Development of candidate models 32

2.3.6 Assessment of the quality of models 32
2.3.7 Variable contribution - Structured Equation Modelling and path diagram. 34
2.4 Comparison of current DBCA post-burn survey data with the patchiness survey 34
Results 36
3.1 Identifying significant correlations between variables and strength of relationships - Pearson correlation analysis 36
3.2 Pre-fire condition variables and fire intensity 40
3.3 Fire intensity variables related to the number of patches and area burnt 42
3.4 Relationship of post-fire vegetation variables with the number of patches and area burnt 44
3.5 Season and its impact on patchiness 46
3.6 Relationship between time since last burn, # veg patches and fire intensity. 49
3.7 Model containing the ‘best’ patchiness creating variables - GLM and Akaike 51
3.8 The final four patchiness creating variables - (SEM) 53
3.8.1 Significant correlations between the dependent and independent variables 53
3.8.2 Significant correlations between the independent variables 53
3.9 Comparison of current DBCA post-burn survey data with the patchiness survey 54
Discussion 58
4.1 Relationships between fire intensity variables and patchiness 58
4.2 Relationship between pre-fire condition variables and fire intensity 59
4.3 Relationship between post-fire fire intensity variables, pre-fire condition variables and patchiness 61
4.4 Patch number and length over spring and autumn 61
4.5 Time since last fire relate to vegetation patches 62
4.6 Variables that strongly indicate patchiness 64
4.7 Comparison between DBCA post-fire surveys and this study 64
4.8 Prescribed burning and possible within-burn homogenisation 65
4.9 Significance of determining within burn patchiness 66
Synthesis and Conclusion 68
5.1 Study’s Limitations 69
5.1.1 Data collection 69
5.1.2 Replication across burn sites 69
5.1.3 Burn Criteria Compliance 70
5.1.4 Comparison of Prescribed fires with Wildfires 70
5.2 Future management recommendations 71
5.2.1 Reducing the fuel load reduction percentage 71

5.2.2 Post-burn survey implementation 71
References 73
Appendix 1. The final field survey data sheet containing the environmental variable that predicts patchiness. 84
Appendix 2. Variable code, name and units of measure. 85

Introduction

1.1. History of fire

1.1.1. The first fire

Fire has been present in forest ecosystems for millions of years (Bond *et al*. 2005), far pre-dating the arrival of humans (Burrows *et al*. 2010). Before the existence of terrestrial plants and photosynthetic organisms on earth, the atmosphere lacked both fuels and oxygen, thus fire could not occur (Pausas & Keeley, 2009). The Paleozoic Era (540 million years ago) presented sufficient oxygen levels to support fire, however still lacked a sufficient fuel source (Pausas & Keeley, 2009). Fossil charcoal indicates that the first wildfires occurred shortly after the appearance of terrestrial plants, 420 million years ago in the Silurian (Bowman *et al*. 2009). Earth history shows that in succeeding years, there has been a correlation between the occurrence of wildfires and the variation in O_2 levels (Pausas & Keeley, 2009; Bowman *et al.* 2009), with combustion taking place when atmospheric O_2 concentrations are above 13% (Bowman *et al.* 2009).

Before the mid-Holocene, lightning was the most common cause of wildfire ignitions in California, USA (Stephens *et al*. 2007) and was presumably present within Australia at least 3 million years ago (Atahan *et al*. 2004). As human populations increased, fire ignitions by Native Americans (Stephens *et al*. 2007) and indigenous Australians became more common (Jurskis, 2005). Native Americans, who relied on a hunter-gatherer existence, used fire as a land/resource management tool (Keeley, 2002). Fire was used to increase seed, bulb and fruit production, increase habitat for mammal resources, reduce hazardous conditions, increase water resources, facilitate travel, and convert coastal/chaparral sage shrub to grassland to increase animal and food supplies (Keeley, 2002). Similarly, Indigenous cultures in Australia historically used fire as a means to improve hunting, wildlife control, promote food resources and increase land access (Penman *et al*. 2011). Today, many indigenous Australian cultures still carry out burning practices, however to a lesser extent than seen in history (Penman *et al*. 2011).

Australia is the most fire prone continent on earth and varies in vegetation type from tropical savannas in the north to tall open forests in the temperate south (Bradstock, 2010). However, contrary to these fairly moist environments, the majority of the Australian environment is dry, arid or semi-arid (Bradstock, 2010; Bradstock *et al*. 2012b). The drivers of fire regimes within each region is relatively well known. Large fires in the southern, forested regions are known to be associated with drought, whereas fires within temperate eucalypt forested areas, are typically driven by variations in litter fuel dynamics, affecting the intensity, season and frequency of forest fires. Arid, central Australia is known to experience large fires due to above average rainfall (Bradstock, 2010). Land management practices, including prescribed burning, are implemented throughout Australia to control these fires (Bradstock *et al*. 2012a).

1.1.2. Prescribed burning and mechanical treatment

Prescribed burning primarily arose for the purpose of reducing the incidence and impact of extensive, high intensity fires (Smith *et al*. 2004; Burrows *et al*. 2010; Grigg *et al*. 2010; Penman *et al*. 2011) on commercial forest values (McCaw, 2013), property and life (Penman *et al*. 2011; McCaw, 2013; Penman *et al*. 2014). Prescribed burning is designed to replace natural fuel – reduction processes (Wittkuhn *et al*. 2011; Stephens *et al*. 2012; McIver *et al*. 2013). Federal forest-fire management began in 1886 in the United States, and by 1891 the suppression of forest fires was considered of high priority, situated at the top of the early forest policy priorities (Stephens & Ruth, 2005). In southeast US, as a result of the need to reduce fuel hazards, the fire policy changed and in 1943 the first prescribed burn was conducted on federal lands in Florida's Osceola National Forest (Stephens & Ruth, 2005). In 1954, wildfire alleviation via prescribed burning became part of State Government policy in southwest Western Australia. This policy however was not completely implemented until the 1960s (Wittkuhn *et al*. 2011).

Even though prescribed fire is perceived as a positive solution, the practice is limited in the United States due to administrative, social and economic influences upon forest managers. In response to these issues, fuel reduction by means of mastication and forest thinning, also known as a mechanical fuel treatment, has increased and become more favoured over prescribed burn practices within many parts of the USA (Stephens *et al*. 2012; McIver *et al*. 2013). Fuel reduction surrogates such as mastication and thinning appear to produce a similar stand structure outcome as prescribed burns (Stephens *et al*. 2012; McIver *et al*. 2013).

Prescribed burning is an efficient and successful treatment for reducing the threat of crown fires by reducing both surface and ladder fuels (Stephens *et al*. 2012), as well as effectively reducing the quantity and intensity of wildfires in Australia (Bradstock *et al*. 2012a). Active crown fire frequency can be reduced via a combination of both mastication and thinning and prescribed fire treatments (Stephens *et al*. 2012). However, prescribed fire treatments alone are capable and sufficient in reducing fuels necessary for crown fires (Stephens *et al*. 2012).

Mechanical treatments are effective but are not capable of achieving some management actions without the assistance of prescribed burning (Stephens *et al*. 2012). For example, mechanical fuel treatments cannot mimic fire in systems with fire-cued recruitment species, and as such, an application of both prescribed fire and mechanical treatments is required (Stephens *et al*. 2012). Fuel reduction costs range from $100s to $1000s of dollars per hectare (Kocher, 2012; Stephens *et al*. 2012) depending on frequency, site size, conditions (Liu *et al*. 2010), terrain, method, location and type of material to be removed (Kocher, 2012). Mechanical treatments are generally more expensive than prescribed fires (Kocher, 2012; Stephens *et al*. 2012).

One advantage of prescribed burns compared to other (surrogate) treatments is that burnt receptive seedbeds can be produced post fire (Van der Meer *et al*. 1999). Shelterwood-treated coupes in Jarrah forest are commonly burnt post-harvest for the purpose of promoting seed fall and to produce a receptive seedbed to encourage seedling regeneration (Bell *et al*. 1989; McCaw,2011; Cargill *et al*. 2016). A receptive seedbed is a forest floor that has a distribution of ash and has experienced the removal of understory vegetation, leaf litter and woody fuels as an outcome of fire (Chambers & Attiwill, 1994; van der Meer *et al*. 1999; Neyland *et al*. 2009; Bailey *et al*. 2012). Not only does a receptive seedbed eliminate competition from undesired species, increase nutrient availability and reduce soil allelopathic compounds (Adams *et al*. 2003; Certini, 2005), but it has also been reported that receptive seedbed conditions are essential for the successful establishment of eucalypt seedlings (Chambers and Attiwill, 1994; van der Meer *et al*. 1999; Neyland *et al*. 2009).

Fire is important for the development of several plant communities within Australia (Morley *et al*. 2004). As a result of years of exposure to fire, some species have evolved and possess fire resilience and resistance traits such as thick protective bark, serotiny, the ability to re-sprout post fire, and germination instigated by smoke and heat (Dixon *et al*, 1995). Plant species that have been found to regenerate by seed post fire require adequate fire intervals in order to attain reproductive maturity, and thus are sensitive to fire frequency (Smith *et al*. 2004). Fires are an essential feature of Jarrah forests and prescribed burning can be used as a suitable management tool in these forests to mimic natural processes while achieving the goal of reducing the occurrence of wildfires (Burrows *et al*. 2010).

1.1.3. South-west Western Australia forest biodiversity

South-west Western Australian forests are rich in biodiversity and are part of a global biodiversity hotspot (McCaw *et al*. 2011). The Jarrah forest flora and fauna represent an important element of this biodiversity, exhibiting a high level of endemism. While many plant species within the south-west forests have a conservation status of rare, there are still many more which we know very little about (McCaw *et al*. 2011). These forests also provide essential habitat and a refuge for several vertebrate species which were once widespread and have since become more isolated in distribution post European settlement. These include the tammar wallaby (*Macropus eugenii*), woylie (*Bettongia penicillate*), chuditch (*Dasyurus geoffroii*) and numbat (*Myrmecobius fasciatus*) (McCaw *et al*. 2011).

The isolation and loss of medium-sized digging mammals has important impacts on fire regimes (Fleming *et al.* 2014). Digging mammals play central roles in ecosystem processes including enhancement of plant growth and recruitment, providing habitat, turnover of organic matter into the soil and away from flames, as well as speeding up the breakdown of organic matter, resulting in reduced fuel loads. The reduction in medium-sized mammals over Australia is said to have potentially increased fuel loads and affect fire regimes as the amount of combustible plant material within the landscape is increased (Fleming *et al.* 2014).

1.1.4. Forest heterogeneity

Within-stand heterogeneity of forests may have been produced through temporal and spatial variation in fire regime, as well as topographic and local environmental variability (Knapp & Keeley, 2006). Wardell-Johnson & Horwitz, 2000, suggest that heterogeneity "provides the foundation for the diversity of habitats and microhabitats and the organisms found within them". Heterogeneity in the physical environment occurs at a range of temporal and spatial scales (Wardell-Johnson & Horwitz, 2000). Spatial heterogeneity is an essential component of forests, promoting the diversity of both fauna and flora (Knapp & Keeley, 2006).

The spatial dispersion of prescribed burning, mining and logging in Jarrah forest has resulted in a mosaic of successional stages, consisting of old growth (unlogged), old and young regrowth, forest burnt in autumn or spring, and long unburnt forest (Abbott *et al*. 2003). A Jarrah forest ecosystem, unburnt for 9 – 18 years and unmined, exhibits high and variable fuel loads (Smith *et al*. 2004). Jarrah forests are known to present several fuel ages and strata levels at multiple spatial scale (Burrows, 2001; McCaw *et al*. 2012).

In the 1870s, Western Australian forests were commercially exploited for timber (McCaw *et al.* 2011). This was predominantly unregulated until the proclamation of the Forests Act of 1918. The Forests Act saw the implementation of permanent areas of state forest as well as funds and staff to carry out significant management activities including silvicultural treatment, fire control and timber industry regulation (McCaw *et al.* 2011). The historical uncontrolled logging led to an increase in forest floor fuel loads and future fires had a negative impact on young Jarrah regrowth (Grigg *et al.* 2010).

1.1.5. Pyrodiversity in forest systems

Prescribed burning has been shown to benefit the environment in many ways, including the generation of a mosaic of successional stages across the landscape (Abbott *et al*. 2003). Pyrodiversity is defined by Tingley *et al*. (2016) as the idea that landscapes with greater heterogeneity in age, size and severity of post-fire patches would support a greater diversity of species. Fire regimes are made up of several different components, including size, spatial configuration, frequency, seasonality and intensity (Morgan *et al*, 2001; Tingley *et al*. 2016), all of which facilitate pyrodiversity and play interactive or independent roles in governing biodiversity assets of the post-fire forests (Tingley *et al*. 2016).

The pyrodiversity – biodiversity hypothesis has gained acceptance (Tingley *et al*. 2016) due to the increased focus in ecological studies on the variability and heterogeneity of responses generated as a result of disturbances (Davies *et al*. 2012). This focus is most prominent within the biodiversity conservation, land and fire management areas (Tingley *et al*. 2016) and includes a consideration of the need to increase fire variability in the landscape (Davies *et al*. 2012). Pyrodiversity – biodiversity relies on the assumption that 'pyrodiversity begets biodiversity' (Davies *et al*. 2012; Griffiths *et al*. 2015; Tingley *et al*. 2016), in other words, an increase in the variability of fire regimes, intensities and patterns (i.e. heterogeneity) will ensure the maintenance of biotic diversity (Davies *et al*. 2012; Maravalhas and Vasconcelos, 2014; Griffiths *et al*. 2015). This assumption is expected, as heterogeneity is known to create more ecological niches and greater number of habitats for species to fill (Holland and Bennett, 2007; Bisigato *et al*. 2009).

Several studies have tested the pyrodiversity-biodiversity hypothesis, however, the results vary with some stating that their findings support or strongly support the pyrodiversity-biodiversity hypothesis (e.g. Maravalhas and Vasconcelos, 2014; Griffiths *et al*. 2015; Ponisio *et al*. 2016) while others found little or no evidence to support the hypothesis (e.g. Davies *et al*. 2012; Taylor *et al*. 2012; Kelly *et al*. 2014; Andersen *et al*. 2014). To date, pyrodiversity has been largely explored at the landscape scale, despite the lack of quantitative methods and monitoring to characterize pyrodiversity at the landscape level (Faivre *et al*. 2011).

Pyrodiversity has mostly been considered a landscape scale phenomenon (Taylor *et al*. 2012; Maravalhas and Vasconcelos, 2014), however, the concept can also be relevant within a focal area or within the perimeter of an individual burn (Tingley *et al*. 2016). Small, moderate intensity fires are capable of producing numerous patches within an area, creating a heterogenous vegetation structure. In contrast, large, intense fires can homogenise the vegetation structure (Griffiths *et al*. 2015) as a result of extensive areas of 'clean' burn. Patches are mostly produced from smaller fires with variable fire intensities creating areas of unburnt habitat (vegetation refuge) together with high-severity areas showing complete habitat and vegetative loss within the perimeter of a single fire (Tingley *et al*. 2016). In addition, Tingley *et al*. (2016), found that individual fires with a greater variety of burn severities have significantly more bird species than areas experiencing fires with more homogenous fire intensities. Immediately after a fire, patches presenting different burn severities had similar bird communities, however, after 10 years bird communities in differing burn severity patches appeared to become dissimilar (Tingley *et al*. 2016). As expected, it was found that the effect of pyrodiversity on biodiversity was greatest 10 years following fire as opposed to the first year post fire (Tingley *et al*. 2016). Within this thesis, pyrodiversity is defined as the patchiness in forest structure created by the heterogeneity in burn severity, within a burn perimeter (not landscape).

Fire intensity varies within a fire as a result of changes in weather, topography, fuel loads and substrate (Tingley *et al*. 2016). Each individual prescribed burn has a set of burn objectives and success criteria. The success criteria generally state the minimum and/or maximum percentage of area that is required to be burnt as well as ensuring that a mosaic of scorch heights and fire intensities are achieved within the burn perimeter (M Pasotti, 2014 pers com). Under the right conditions, prescribed burning can meet these criteria and create a mosaic of fire intensities within a burn perimeter, however, variations in fuel loads, topographic and biotic factors may cause some prescribed burns to potentially burn more intensively than expected (M Pasotti, 2014 pers com). It is thus possible that, under the right conditions, a prescribed burn can result in a fire of high intensity and therefore could potentially have a homogenizing effect across the total area within the perimeter of the burn.

1.2. Fire characteristics

Fires are characterised by several factors including: fuel properties, structure and combustion, chemical and physical properties of emissions and flames, thermal degradation, and wind, atmospheric and slope interactions (Wotton *et al*. 2012). There are many types of fires, all of which have the potential to alter ecosystem processes, creating temporal and spatial changes in fuel accumulation, species structure and composition (Burrows and Wardell-Johnson, 2003). Fires may be crown fires (canopy fire), surface fires (fire in the understory shrubs and litter layer), and subterranean fires (fire in organic layers of the soil) (Bond and van Wilgen, 1996). Wildfires are characteristically larger than prescribed fires and are potentially more variable and intense, particularly if they burn over many days (Leonard *et al*, 2014; Alba *et al*. 2015). Measuring fire characteristics is accomplished through the assessment of flames. Flames are continuously changing in shape and size, and therefore are complex phenomena which can not only describe the character of a fire but its behaviour and effects as well (Wotton *et al*. 2012).

1.3. Fire behaviour

It is known that a large variety of factors affect the rate of spread of fires; these include weather (relative humidity, wind-speed and temperature), topography (slope steepness, terrain shape), fuel moisture content, and the type, size, quantity and spatial distribution of fuel (Gosper *et al*. 2014). These factors contribute and influence the rate of spread of a fire and thus influence fire intensity (Alexander & Cruz, 2012). The fuel moisture levels, amount of fuel available and the combustion rate predominantly determines the intensity of a fire (Grigg *et al*. 2010); low fuel moisture levels and a large quantity of available fuel will generally result in high fire intensity (Smith *et al*. 2004).

Crown scorch height and flame height are also linked to fire intensity (Alexander & Cruz, 2012). Spotfire's are the principal mechanism by which wildfires breach barriers such as firebreaks and roads, and are one of the reasons why it is difficult to calculate the spread of the surface-fire accurately, as the spotting causes the rate of the fire to move at a much faster rate (McCaw *et al*. 2012). Under extreme weather conditions, landscape fuel treatments such as fire breaks are unlikely to have a significant impact on the risk that wildfires present to assets and lives. Managing the occurrence of fire (prescribed burning) as well as the spatial distribution of the built environment (such as distance to road, distance to structure and housing density) may alter the risk profile (Penman *et al*. 2014).

Forest fire behaviours such as spotting, forward rate of spread, crowning and flame height can be predicted in Australian fire forest operations within dry eucalypt forest using either of the two available fire danger rating systems otherwise known as behaviour guides: Forest Fire Behaviour Tables for Western Australia (FFBT) and the Forest Fire Danger Meter (FFDM) (McCaw *et al*. 2008; Cheney *et al*. 2012). These models were designed to predict the behaviour of prescribed burn fires, and as such, were developed using data from small prescribed burns ignited in open eucalypt forest with fuel comprised of sparse low shrubs and leaf litter. Although primarily aimed at prescribed fires, the guides along with observations of the spread of wildfire, have also been used to predict the behaviour of high-intensity fires (Gould *et al*, 2008).

Evidence has shown however, that both the FFDM and FFBT fire spread models under-predict the rate of spread of larger, more intense fires and that the most accurate predictions were made when shrub fuels were sparse and winds were light (<12 km h^{-1}) (McCaw *et al*. 2008). Gould *et al*. (2008), designed a model to predict the potential rate of spread of a high intensity fire in dry eucalypt forests with a native understory of shrubs. This model is said to be applicable to any eucalypt fuel dominated by an understory of native shrubs, leaf litter and small amounts of grass (Gould *et al*, 2008).

Weather also has a strong influence on a fire intensity and severity, the rate of spread, size and spotting distance (Penman *et al*. 2014). In some countries, wildfire risks are assessed by the use of the Fire Weather Index (FWI) System. Weather conditions such as solar radiation, drought and wind-speed, along with other factors such as topography, fuel accumulation, vegetation type and human factors (ignition factors and land use) determine wildfire activity (Mori & Johnson, 2013).

1.4. Fuel

Forest fuels are defined by the physical characteristics of dead and live vegetation that contribute to wildland fire behaviour (Gould *et al.* 2011). Physical characteristics include particle size, loading, height, depth, and bulk density (Gould *et al.* 2011). Fuels can be categorised into the following groups (Stephens *et al*. 2012; Wotton *et al*. 2012):

- Crown fuel – overstory canopy, tops of the tallest trees and associated bark
- Ladder fuel – tall shrubs, intermediate trees and bark fuel
- Surface fuel – small shrubs, litter, herbaceous plant material, grasses, bark, twigs and suspended leaves
- Ground fuel – duff on the soil surface

Each of these groups can influence fire behaviour in a different way. Crown fuels, depending on the forest and area, may or may not be a small component of fire hazards (Stephens *et al*.

2012). The vertical distribution of fuels (ladder fuel) is very important in sclerophyll forests (Smith *et al*. 2004) and are the second most hazardous fuel group (Stephens *et al*. 2012) as they create a continuous fuel source (Smith *et al*. 2004, Stephens *et al*. 2012), which is important for the development of crown fires (Smith *et al*. 2004). Surface fuels are generally the most hazardous fuel group in numerous forests and ground fuels usually do not contribute to wildfire intensity or spread (Stephens *et al*. 2012).

Fuel characteristics including height, visual structure and load, together with wind-speed, are associated with firebrand density, fire spread, spotting distance and flame height. These factors increase in importance with time since last fire (McCaw *et al*. 2012). The size, depth of fuel, distribution and density of understory vegetation will dictate the intensity of fire (Bond & van Wilgen, 1996; McCaw, 2011). Climate affects the quantity and type of fuel as well as the seasonal fuel moisture through variations in humidity, rainfall and temperature. This is essential knowledge as fuel moisture determines the rate of combustion and flammability of course woody debris (CWD) which in turn influences the rate of fuel consumption and fire spread (Gill *et al*. 1981).

Fuel load (mass per unit area) is used to predict fire behaviour (McCaw *et al*. 2012). Within *Eucalyptus* forests, the most significant fuel variable influencing the spread of fire is the quantity of fine fuel (<6 mm diameter) present on the forest floor (McCaw *et al*. 2012). McCaw (2012) suggests that within eucalypt forests, the rate of spread of a fire is directly proportional to fine fuel load; if the fuel load is reduced by 50%, the rate of spread is halved, thus reducing the intensity of a fire.

1.5. Jarrah forest structure and characteristics

Eucalyptus is the second largest flora genus in Australia with approximately 800 species, subspecies and varieties (French, 2012). In south-west Western Australia, open forests are known to have a mature height exceeding 10 m (McCaw *et al.* 2011). More than 85% of the forest in the south-west is on public land and managed by the Parks and Wildlife Service, part of the Department of Biodiversity, Conservation and Attractions (DBCA) as conservation reserve and multiple-use state forest (McCaw *et al.* 2011). Eucalypt species dominate these forests with Jarrah *Eucalyptus marginata* being the most widespread (1.8 million ha). Jarrah (*Eucalyptus marginata*) forests support a rich biodiversity that is of national and international significance (McCaw *et al.* 2011). Forest trees including wandoo (*E. wandoo*), marri

(*Corymbia calophylla*), tuart (*E. gomphocephala*) and karri (*E. diversicolor*) are also dominant (McCaw *et al.* 2011).

Dry sclerophyll Jarrah (*Eucalyptus marginata*) forests in the south-west Australian region have been noted to vary in structure and floristic characteristics, including in the number of strata in response to climate and soil/landform factors (Bell & Heddle, 1989). McCaw *et al*. (2012) and Wotton *et al*. (2012), reported on Jarrah forest structure in the same two areas, the first site at McCork hill containing five fuel ages, the second at Dee Vee Road presenting four. Strata levels were as follows:

- Crown cover of 30-50% and a maximum height of 25-30 m; comprising of marri (*Corymbia calophylla*) and Jarrah (*Eucalyptus marginata*)
- Intermediate layer (≤ 5 m tall) contained marri and Jarrah saplings as well as Banksia *grandis* and *Allocasuarina fraseriana*
- Understory – the two Jarrah forest sites had contrasting understories,
  - First site: fairly dense understory of shrubs, 0.2 to 3 m tall, dominated by *Taxandria parviceps*. Coverage - sparse to near continuous, varying due to time since last fire.
  - Second site: dominated by a sparse cover of low shrubs, *Bossiaea ornata* (0.5 m tall). *Bossiaea ornata senesces* after 3 years, leaving a surface layer largely consisting of twigs, leaf litter and bark (McCaw *et al*. 2012).

Variations in the region's climate and soil alters forest understory composition and structure and as a result, the quantity of fuel created is temporarily and spatially variable (McCaw *et al*. 1997; McCaw *et al*. 2008). Rainfall also impacts on the structure of Jarrah forests in Australia; on the basis of canopy height and density, forests in dryer climates, i.e. north and east, are classed as open forest, low forest and woodland due to a decrease in stature as a result of low rainfall while Jarrah forest in southern, higher rainfall areas, are classed as tall forest (Dell & Havel, 1989).

Another influence on Jarrah stand structure and species composition is dieback disease caused by *Phytophthora cinnamomi* (McCaw, 2011). *Phytophthora cinnamomi* is an exotic soil-borne pathogen that kills certain flora species, including Jarrah, by rotting the root system and lower stem tissues. This restricts the plants ability to uptake water and nutrients (Anderson *et al*. 2010). The term 'dieback' is characterised by rapid defoliation and progressive stem mortality in overstory trees (Rice *et al*. 2004). Dieback can also be defined as a sudden death of trees associated with waterlogging, root rot or drought (Rice *et al*. 2004). Over the years, *P. cinnamomi* has had an ever-growing impact on eucalypt forests; dramatically reducing the structure, composition and fuel characteristics of infected areas (Anderson *et al*. 2010).

It is well known that fire has had a significant influence in shaping the evolution of Jarrah forest (McCaw *et al.* 2011). During the mid-Pliocene, fires in south-west western Australia occurred at intervals of 5 – 13 years (McCaw *et al.* 2011). Plants of the Jarrah forest have evolved in the presence of fire, and have developed multiple plant morphologies and mechanisms, such as lignotuberous resprouting, fire ephemerals, obligate seed regeneration, and rapid post fire flowering, all of which enables these species to persist and survive in an environment characterised by frequent fires (Gill *et al*. 1981; Burrows and Wardell-Johnson, 2003). Jarrah forests exhibit distinct structural changes and multiple age cohorts of trees as a result of differences in fire histories (Pekin *et al*. 2009). It wasn't until the mid-1950s that fire management practices first began in jarrah forest which focused on rapid fire detection, fire prevention, suppression forces, and prescribed burning practices to reduce fuel loads and promote both understory and tree regeneration (McCaw *et al.* 2011).

1.6. Patchiness within a single burn

Pyrodiversity within a burn, seen as the number and size of post-fire patches km^{-1} present after a burn, is a consequence of variation in fire severities (Tingley *et al*. 2016). Patchiness is further defined as the spatial configuration of unburnt and burnt patches which occur at a range of spatial scales (Oliveira *et al*. 2015). In this study, the level of patchiness is assessed at a fine-scale or within-fire level rather than the more usual landscape level consideration. Studies have shown that there is a positive link between fire patchiness and biodiversity, most of which have been conducted on a landscape scale (Oliveira *et al*. 2015). Few studies have been undertaken on the link between biodiversity and within-fire patchiness, although a recent study by Sitters *et al*. (2015), showed that many bird species responded positively to increased patchiness in tall eucalypt forest in SE Australia while Tingley *et al*. (2016) found that a decade post fire there were significantly more bird species in areas that had experienced variable within-fire intensities. Unburnt patches within a fire perimeter may also be important refugia for species which strongly prefer or require unburnt habitat (Burrows, 2008).

1.7. Prescribed burns and current post-burn assessments

1.7.1. Parks and Wildlife Service prescribed fire protocols

This study focusses on prescribed burning within the northern Jarrah forests of Perth, Western Australia, where the Parks and Wildlife Service, part of the Department of Biodiversity, Conservation and Attractions (DBCA) carry out prescribed burns with the objective of reducing risk to life and property while enhancing biodiversity outcomes.

A fire regime can describe the occurrence and frequency of fire, and the intensity, extent and season of occurrence (Smith *et al*. 2004). Fire regimes generally have four interrelated components: fire intensity (heat output from fire), fire frequency, area of burn, and season of fire (time of year) (Gill *et al*. 1981; Bond and van Wilgen, 1996; Smith *et al*. 2004). Fire regimes can be influenced by components that can be directly manipulated such as fuel loads and vegetation structure, as well as by selecting suitable weather conditions for the burn. This ability to control fire is the major rationale behind the practice of prescribed burning carried out in Australian forests (Smith *et al*. 2004).

In dry eucalypt forest fuel accumulates for approximately 5 – 8 years, after which time the rate of accumulation declines and fuel loading stabilises (Gould *et al* 2011). Based on these fuel accumulation rates, prescribed burns are undertaken in Jarrah forest understory in a mosaic pattern on a rotation of 5 – 12 years (Smith *et al*. 2004; Grigg *et al*. 2010). This may be different in other parts of the forest (increase or decrease in fire intervals) depending on management objectives (Burrows *et al*. 2010), such as silviculture, as well as the rate of fuel recovery and other considerations (Grigg *et al*. 2010).

Prescribed burns within the forests of south-western Australia are usually carried out in autumn (around April) or spring (around October) (Smith *et al*. 2004; Grigg *et al*. 2010; DPaW, 2013) as fires in summer and late autumn are usually more intense because fuel moisture levels are low (Smith *et al*. 2004). In Western Australian, Jarrah (*Eucalyptus marginata*) forests have been managed by the Parks and Wildlife Service and its precursors (Forestry Dept, CALM, DEC, DPaW) since 1954. Parks and Wildlife Service's primary management tool in reducing fire hazard in Jarrah forests is to conduct low intensity fuel-reduction controlled burns (Smith *et al*. 2004).

1.7.2. Prescribed burn planning process

Each individual controlled burn involves careful and deliberate planning (DPaW, 2013) that includes the development of a burn program, a prescribed fire plan (prescription) for each burn, implementing the burn, and finally a post-burn assessment (DPaW, 2013). Planning must consider all possible issues including dieback, rare flora, fauna species habitat, smoke impacts on local communities, using fire for silviculture (i.e. regeneration) and mining rehabilitation. When it comes to planning and implementing a burn, weather is a key factor in deciding whether to proceed with the burn or not (DPaW, 2013).

1.7.3. Prescribed burn categories

Prescribed fires are designed and implemented to meet a set of desired outcomes, including biodiversity conservation, vegetation management, research, community interest, managing water catchment productivity, silvicultural burns for regeneration of native forest following harvesting, and community protection such as life, property, parks, water catchments, plantations, timber values and public assets (DPaW, 2013).

1.7.4. Prescribed Fire Plan – Success criteria and Objectives

Success criteria and objectives proposed in the prescribed fire plan vary between burns (M Pasotti, 2014 pers com). The majority of burns have fairly simple fuel reduction and overall landscape fuel age mosaic (biodiversity) objectives. These usually refer to the extent of the area burnt and some estimates of fire intensity. Burns that are carried out in close proximity to assets/infrastructure will have a target that specifies a greater percentage of the area to be burnt than those in more remote areas (M Pasotti, 2014 pers com). Burns that have silvicultural objectives or are implemented to stimulate seed fall from dominant trees may have greater fire intensity requirements than those required to protect the crowns of remaining trees. Thus, fire intensity depends on the desired future silvicultural use of that particular section of forest as well as the harvest treatment type (M Pasotti, 2014 pers com). Burns with priority or rare fauna or flora present that have specific fire regime requirements may have other success criteria that relate to fire intensity to stimulate germination of the seed bank or relate to exclusion zones around habitat areas. These success criteria vary depending on the target species. Other burn objectives may relate to community interest, water catchment, research, and rehabilitation outcomes and each of these will also have different success criteria (M Pasotti, 2014 pers com).

1.7.5. Post burn assessment

Post-burn assessment is carried out after each burn in which burns are assessed against the success criteria and objectives given in the prescribed fire plan. Assessment approaches may include:

- Ground surveillance – assessment completed via vehicle or on foot. This method is used to estimate and evaluate the success of the burn against the stated success criteria and objectives
- Aerial surveillance – visual assessment from the air or ground. Use of photographs or hand drawn maps to determine if the vegetation mosaic criterion was met.
- Satellite imagery – used to map fires using LANDSAT and MODIS imagery. This method is dependent on many factors and is mostly used for extensive fires in remote areas.
- Airborne scanners – used for autumn, post-burn assessment in southern areas of Western Australia (DPaW, 2013).

The use of these methods depends on burn locality, data required, weather conditions and size of the burn area (DPaW, 2013). Post-burn assessment of fuel reduction/biodiversity burns within Perth hills Jarrah forest involves an assessment of basic parameters such as area burnt (broad visual estimate of overall % burnt vs unburnt) and approximate intensity (general scorch height) (M Pasotti, 2014 pers com). These data are collected via ground surveillance, aerial mapping or aerial scanning and occasionally from satellite. The method of capture depends largely on the size and complexity of the burn with visual observations/surveillance and estimates used in small-scale burns (generally hundreds of hectares or less in size) and aerial mapping used for larger burns (generally thousands of hectares in scale). This assessment is for a simple fuel reduction/biodiversity burn however, if more complex objectives are required (i.e. specific habitat requirements, priority or rare species) then more detailed monitoring of target areas may be carried out. This may involve pre-burn and post-burn fauna habitat surveys and/or population estimates or flora population surveys. Areas with rare species will almost always have a pre-burn survey and post-burn follow up monitoring, which usually occurs over several years following a burn (M Pasotti, 2014 pers com).

Most post-burn assessments are carried out once, with the exception of the above-mentioned flora/fauna specific monitoring. Most of the information/data can be obtained from a single inspection (estimates of area burnt and fire intensity). For a simple small biodiversity/fuel reduction burn, post-fire surveillance via ground observation is completed by visual estimates (M Pasotti, 2014 pers com). This estimate is added to the documented prescribed fire plan as part of the post-burn assessment section prior to the prescription being closed. Once a burn has been completed there is little that can be done to change the outcome (M Pasotti, 2014 pers com). If an area that was meant to be burnt has not burnt, i.e. the percentage of area burnt is too low, fire can sometimes be re-applied to that section of the burn if the season allows it and it is not going to add risk to the burn. However, if areas that were intended for exclusion are burnt, then there is little that can be done other than recording the issue and identifying why the planned exclusion strategy did not work (M Pasotti, 2014 pers com).

Since fire behaviour is a complex interaction of seasonal conditions, local-scale weather influences and site-specific fuel arrangements, it is virtually impossible to achieve very specific outcomes, as fire behaviour will change as it moves across an area (M Pasotti, 2014 pers com). Parks and Wildlife Service are very fortunate that most communities and species are well adapted to fire and can accommodate a wide range of fire types and regimes at a landscape scale (M Pasotti, 2014 pers com; Burrows *et al*. 2010; Smith *et al*. 2004). Therefore, fire prescription parameters are usually fairly broad to allow for local variation, unless there is a particular issue that requires a specific outcome (M Pasotti, 2014 pers com).

Remote sensing has been used in fire-burnt landscapes, with some uses being to map the extent of the burn, quantify the pattern of the burn areas, and understand the biological responses due to varying fire severity (White *et al.* 1996). Physical changes caused by fire, including canopy consumption, soil colour alteration, and ground charring, can be detectable using satellite sensors (White *et al.* 1996). Although remote sensing is capable of mapping vegetation post fire (Xie et al. 2008), there are several challenges that come with using this method, including, but not limited to, the level of resolution as well as possible canopy obstruction (Keane *et al.* 2001). This thesis will be looking at small scale vegetation characteristics, including vegetation patches ≥1 meter in size, under canopy possibly un-touched by fire. Due to the high resolution required to obtain the data required (Xie et al. 2008), combined with potential canopy obstruction (Keane *et al.* 2001), all field data surveyed within this thesis will be obtained via ground surveillance.

Pyrodiversity has been largely explored at the landscape scale (Faivre *et al*. 2011), however, there is very little known on the patchiness within the perimeter of a single prescribed burn. In addition, there is limited information about whether a prescribed burn can or does cause homogenisation within a single burn perimeter. Under the right conditions, a prescribed burn can result in a fire of high intensity and therefore could potentially have a homogenizing effect on the within-burn area. The current post-burn assessment used by Parks and Wildlife Service is not specific enough to meet the objectives of this study. Therefore, a post-burn survey was specifically developed for the purpose of this thesis. The following flow diagram summarises the overall layout of this study (Figure 1).

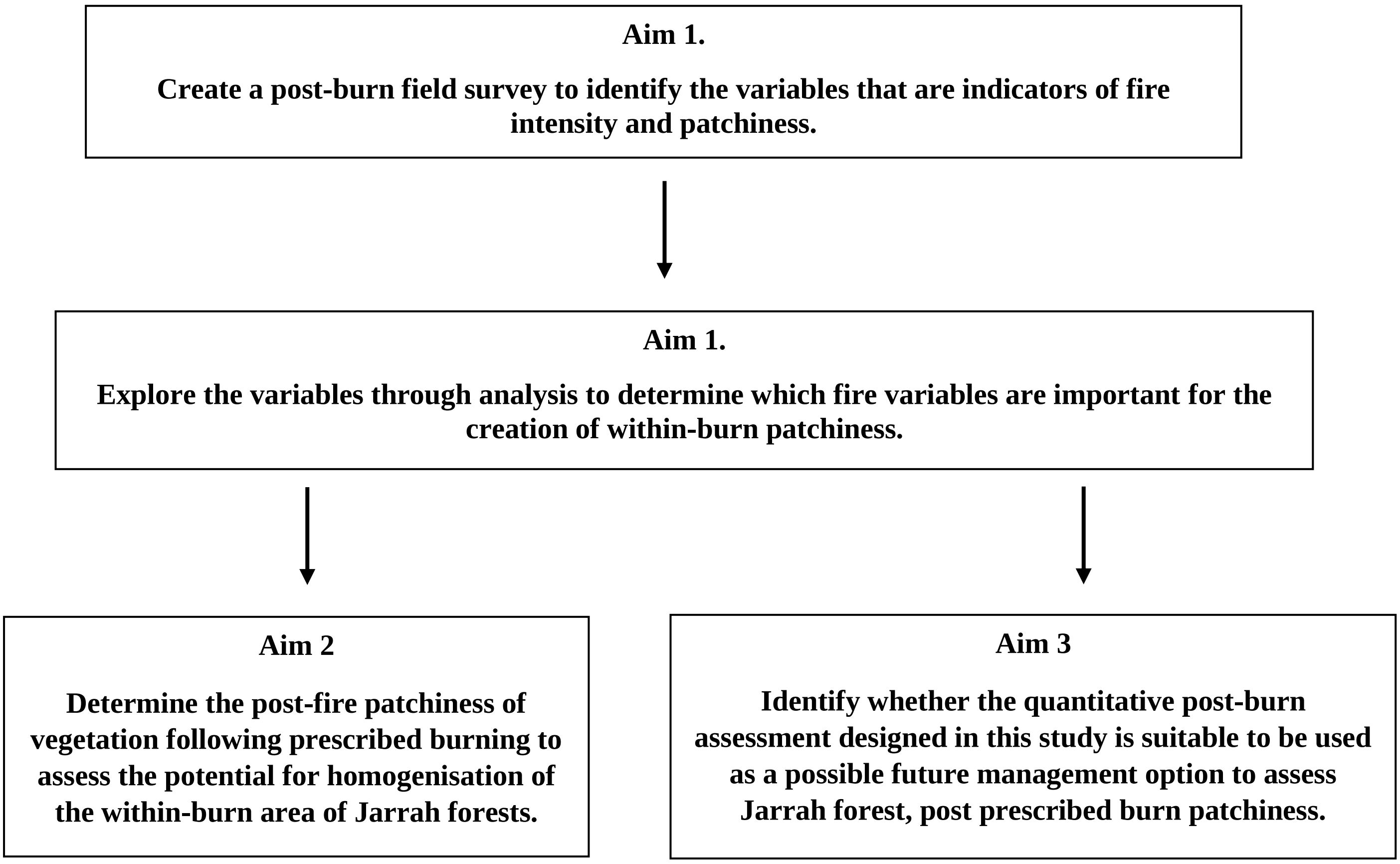


Figure 1. Flow diagram showing an overall summary of the thesis.

Objectives

The overall objective of this study was to determine whether prescribed burning reduced the natural patchiness of fires, leading to the potential homogenisation of the within-burn area of Jarrah forests, which in turn may have long-term implications for biodiversity outcomes. The current prescribed burn assessment method used in the south-west Western Australia Jarrah forest does not gather enough information and data to meet the objective of this thesis. Therefore, the development of a set of post-burn surveys were required and were implemented to determine the patchiness of the burnt areas within a number of prescribed burns. Specifically, this study focussed on within-burn pyrodiversity, which is defined as the patchiness in forest structure created by the heterogeneity in burn severity.

Recording pyrodiversity associated with prescribed fires is essential for any follow up biodiversity impact studies that can be undertaken in the future. However, follow up studies were not possible in the time frame of this project. The results of this study complement current post-burn assessments, as they provide quantitative data to test the ‘pyrodiversity begets biodiversity' paradigm as forests recover from current prescribed burning operations.

This thesis has three specific aims:

1. Identify the variables that are indicators of fire intensity and patchiness and explore them through GLM and structural equation modelling to determine which fire variables are important for the creation of within-burn patchiness.
2. Using the data and information obtained from the first aim, I will determine the post-fire patchiness of vegetation following prescribed burning to assess the potential for homogenisation of the within-burn area of Jarrah forests.
3. Identify whether the quantitative post-burn assessment designed in this study is suitable to be used as a possible future management option to assess Jarrah forest, post prescribed burn patchiness.

Methods

2.1 Selection of Study Sites

Surveys were completed in post-prescribed burn treated areas within the northern Jarrah forests between Mundaring and Dwellingup, Western Australia. A list of potential/planned burns that were considered 'highly likely' of going ahead in 2015 had been compiled by the Parks and Wildlife Service (within the Department of Biodiversity, Conservation and Attractions), Perth Hills District (Fig 2) and was used as a baseline for the selection of potential sites for surveys. Not all the 'potential/planned burn' sites on the map were usable. The sites were required to meet the following criteria to be used in the survey:

1. They needed to be treated with a prescribed burn in the 2015 year,
2. The burn area needed to be >2000 ha, and
3. The vegetation of the prescribed burn areas was restricted to predominantly Jarrah forest (forest dominated by *E. marginata*).

The final decision for a Parks and Wildlife Service prescribed burn to be carried out and implemented in any area was decided the morning of the burn. The environmental conditions on the day of the burn were required to meet a set of conditions (including specific weather conditions, Fire Danger Index (FDI), Surface Moisture Content (SMC), Soil Dryness Index (SDI) and social parameters - smoke management, traffic management) in order for a prescribed burn to be undertaken. Since the prescribed burns were only confirmed on the day of the burn, the location of prescribed burns surveyed (study sites) for this study were unknown until the morning of a burn. This made pre-fire site surveys impossible since a considerable number of planned burns did not go ahead due to unsuitable environmental conditions. A total of 18 post-fire surveys were completed in the autumn or spring of 2015.

The autumn prescribed burning program commenced in April 2015, and the spring burns in September 2015 (M Pasotti, 2015, pers com). Surveys were completed as soon as possible and after the burn was declared extinguished, as a safety measure. A total of 18 study sites were surveyed (Table 1, Fig 3). Survey sites included: PHS_015 Moondyne, PHS_066 Reservoir, PHS_043 Amphion_Plavins, PHS_037 Serpentine NP3, PHS_046 Dale, PHS_020 Zamia, PHS_006 Woondowing, PHS_046 Dale (South Burn), PHS_071 Nockine_Qualen_Dale, PHS_056 Randall 1, PHS_063 Geddes, PHS_034 Serpentine NP 1, PHS_067 Holyoake 1 (28/04/2015), PHS_067 Holyoake 1 (21/09/2015), PHS_060 Victoria 2 (24/10/2015), PHS_060 Victoria 2 (22/10/2015), PHS_060 Victoria 2 (26/10/2015), and PHS_060 Victoria 2 (21/10/2015) (Table 1, Fig 3). PHS_060 Victoria 2 site was burnt over several days, thus each separate burn was surveyed and are indicated by the dates displayed alongside the burn site name. A section of PHS_046 Holyoake 1 was burnt in autumn, the other section in spring, and again these were considered separate burns (as indicated by the date of the burn located next to the burn site name (Table 1)).

Table 1. A list of the 18 survey sites, the area burnt (ha), date of the burn, date the survey was conducted and the time in years since the site was last burnt.

Site no.	Survey Site Name	Area of Burn (ha)	Date of Burn	Date of Survey	Time since last burn (yrs)
1	PHS_015 Moondyne	2514	19/04/2015	11/06/2015	16
2	PHS_066 Reservoir	3739	13/05/2015	16/06/2015	11
3	PHS_067 Holyoake 1 (28/04/2015)	1250	28/04/2015	24/06/2015	10
4	PHS_043 Amphion_Plavins	482	23/04/2015	25/06/2015	27
5	PHS_037 Serpentine NP3	583	13/05/2015	13/07/2015	33
6	PHS_046 Dale	4057	12/05/2015	20/07/2015	32
7	PHS_020 Zamia	293	2/05/2015	25/08/2015	18
8	PHS_006 Woondowing	180	9/09/2015	26/12/2015	Unknown
9	PHS_060 Victoria 2 (24/10/2015)	174	24/10/2015	21/12/2015	10
10	PHS_060 Victoria 2 (22/10/2015)	267	22/10/2015	22/12/2015	10
11	PHS_060 Victoria 2 (26/10/2015)	497	26/10/2015	27/12/2015	10
12	PHS_046 Dale (South Burn)	2684	21/09/2015	02/01/2016	32
13	PHS_071 Nockine_Qualen_Dale	8827	27/09/2015	03/01/2016	10
14	PHS_067 Holyoake 1 (21/09/2015)	2059	21/09/2015	22/01/2016	10
15	PHS_056 Randall 1	5181	18/09/2015	03/02/2016	33
16	PHS_063 Geddes	9855	25/09/2015	06/02/2016	13
17	PHS_034 Serpentine NP 1	177	16/10/2015	30/12/2015	37
18	PHS_060 Victoria 2 (21/10/2015)	93	21/10/2015	29/12/2015	10

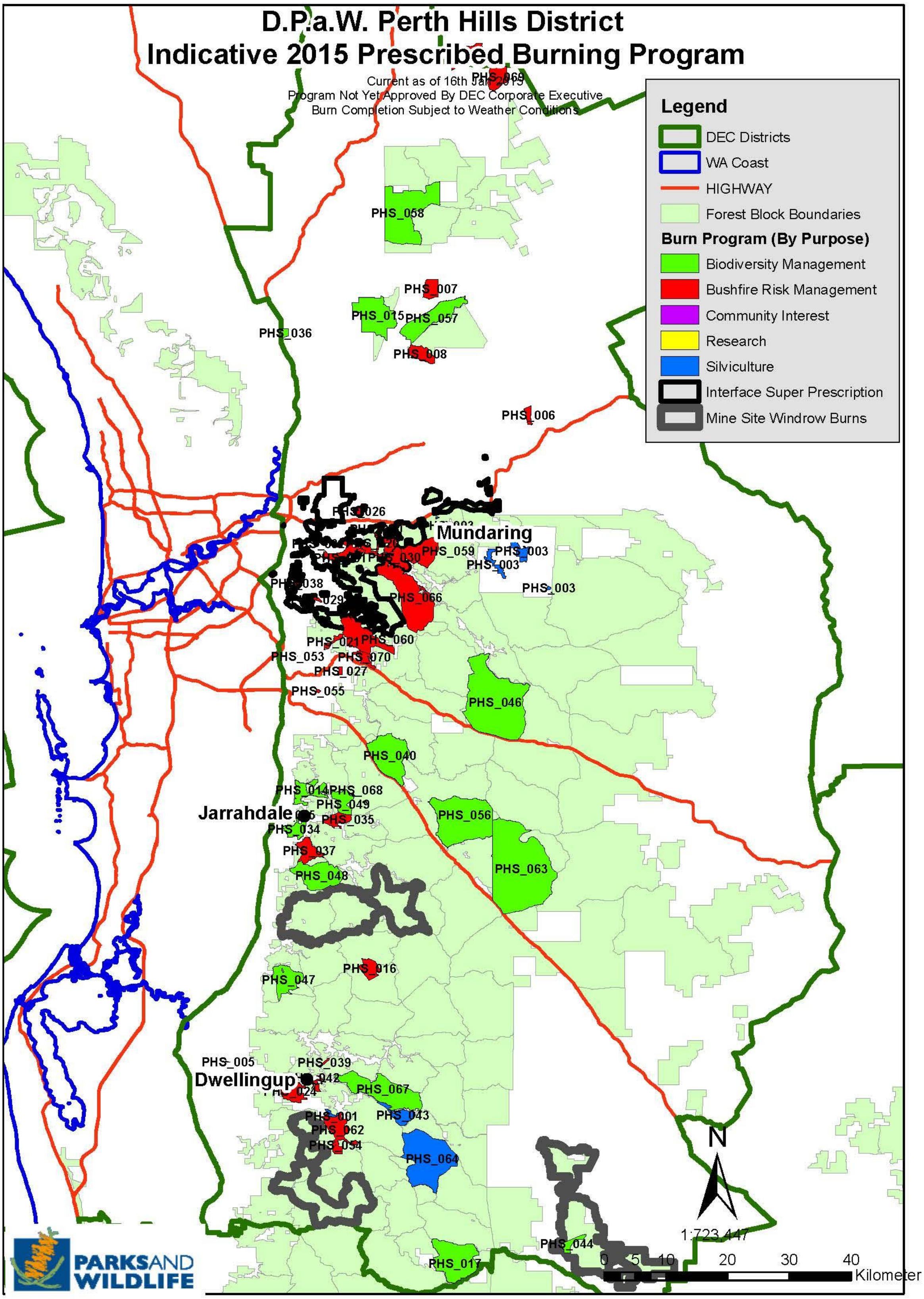


Figure 2. Parks and Wildlife Service, Perth Hills District, indicative prescribed burning program for 2015. Individual/separated burns indicated by the burn date are not shown.

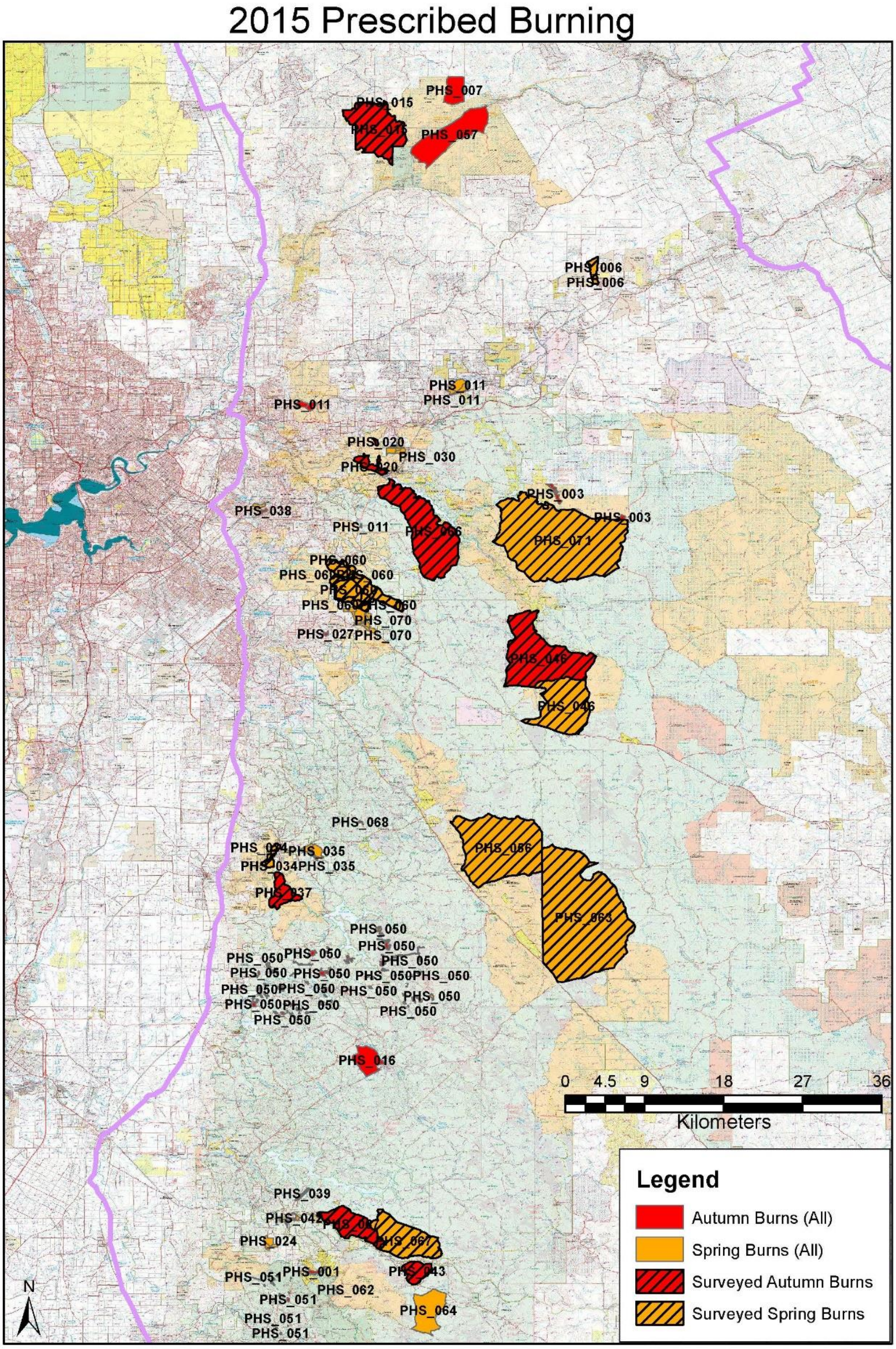


Figure 3. Parks and Wildlife Service DBCA, Perth Hills District 2015 determined prescribed burn sites, including the sites surveyed for this study in autumn and spring. Individual/separated burns indicated by the burn date are not shown.

2.2 Development of survey and field monitoring sheets

2.2.1 Survey Templates

A post-burn assessment survey was designed to gather data on 29 environmental variables. Of these, twenty-four were collected via field surveys, across 18 post-burn sites, and five weather/pre-fire condition variables were obtained from external sources (Parks and Wildlife Service and BOM website). These variables were gathered to capture the variability across an individual prescribed burn to determine the within-burn fire characteristics. To collect the twenty-four environmental variables in the field, a survey was designed. One survey was conducted per prescribed burn area (treated area) and each consisted of three 'templates'. These templates were designed to gather measurements on each of the twenty-four environmental variables efficiently and effectively while capturing the variability in fire behaviour across the treated area. Each template consisted of two 500m line transects and three 20 m x 20 m plots (Fig 4). The two transects made up two sides of the triangular template, the remaining side being the road. A 30° to 45° angle was used to determine the two arms of the transect. This angle maximises the depth of penetration into the treated area as well as providing an approximate 500 m distance between the first and third plots thus increasing the chance of sampling the potential variation in burn characteristics across the whole of the prescribed burn area.

A 20 m x 20 m plot was established at each of the triangles vertices. Transects were walked using a compass and/or GPS. All plot boundaries adjacent to the triangular transects were defined using four stakes, one at each corner, inserted into the ground using a hammer. All plot locations were added as waypoints on GPS and photos of each plot and survey area were taken.

Each of the three templates (per survey) (Fig 4) were placed per 500 ha of treated forest. Templates were at least 500 m apart, this was largely influenced by the size of the prescribed burn area. Treated areas were required to be >2000 ha or the survey design would not fit. Templates were placed according to the topography, shape and size of the treated area in order to obtain any variability that existed across the burn. A buffer of 50m or more was placed between the survey template and roads and any buildings to counteract edge effects.

Survey 1 out of 3

Environmental variable	No. of trees sighted 5m each side of the transect
Habitat trees	

Patch matrix: #Veg Patches

Area Burnt %

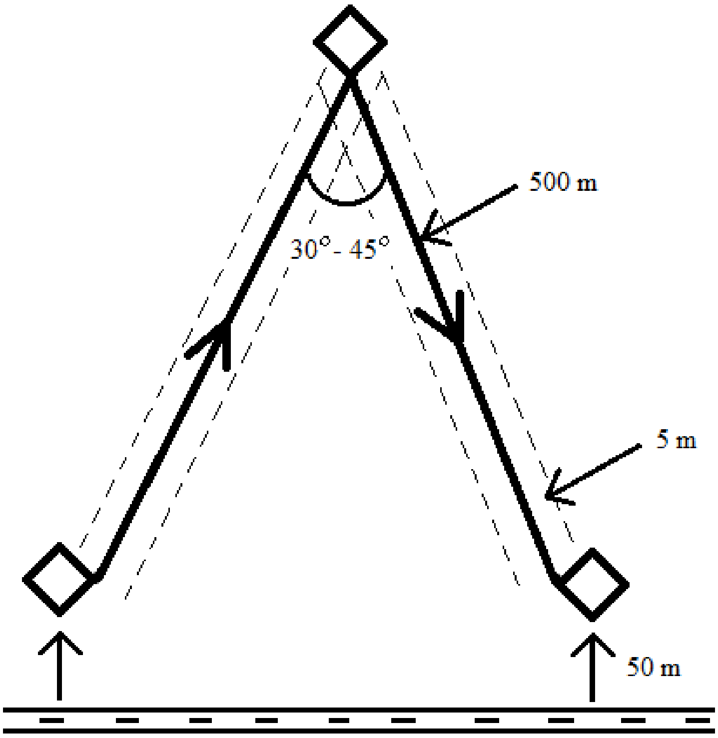
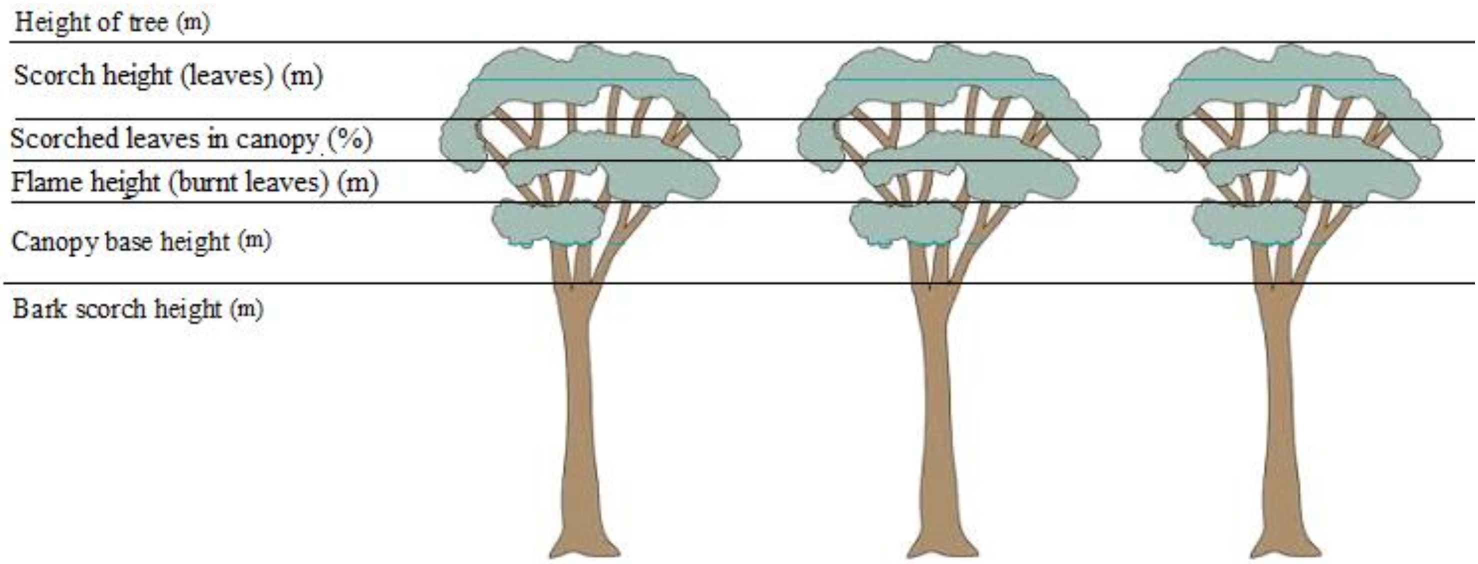


Figure 4. Transect field survey data sheet, 2 per A4 page, 3 required per study site.

Each 500 m transect was walked with visual data collected 5 m each side (Fig 4). Along the line transects, the number of habitat trees (see Table 2 for definition) was recorded as well as the lengths of burnt and unburnt vegetation along the transect line to derive the percentage area burnt and number of patches km^{-1} (Table 2). Data collected within each of the 20 m x 20 m plots were largely visual estimates of habitat features (fully explained in Table 2) and included: the average height of trees (m); average height of scorched leaves (m); scorched leaves in the canopy (%); average height of burnt leaves (flame height) (m); canopy base height (average height from ground to bottom of tree crowns) (m), bark scorch height (m), remaining live leaves in the canopy (canopy cover) (%), understory burnt (%), ground burnt (%), live ground vegetation cover (%), live shrub cover (%), bare earth (%), litter cover (%) and depth (cm), average bole char height (m), cover (%) and colour of ash, cover of orange earth (%), and relative fire intensity (high or low intensity burn) measured as branch thickness (mm). The 20 m x 20 m plot field survey data sheet is shown in Figure 5.



Environmental variable (estimated averages)	Plot 1	Plot 2	Plot 3
Canopy cover	%	%	%
Understory burnt	%	%	%
Ground burnt	%	%	%
Ground vegetation cover	%	%	%
Shrub cover	%	%	%
Bare earth	%	%	%
Litter cover	%	%	%
Litter depth (6 measurements averaged)	cm	cm	cm
Basal char severity [X] (See below for category*)	1 ☐ 2 ☐ 3 ☐ 4 ☐	1 ☐ 2 ☐ 3 ☐ 4 ☐	1 ☐ 2 ☐ 3 ☐ 4 ☐
Cover and colour of ash	White = % Grey = % Black = % Cover = %	White = % Grey = % Black = % Cover = %	White = % Grey = % Black = % Cover = %
Cover of orange earth	%	%	%
Branch thickness remaining [X]	< 25 mm ☐ <25 mm ☐	< 25 mm ☐ <25 mm ☐	< 25 mm ☐ <25 mm ☐

* 0 = no visible charring of bark; 1 = some blackening around base; 2 = bark plate surface uniformly blackened; 3 = some depth of char; 4 = deep char

Figure 5. 20 m x 20 m plot field survey data sheet template, A4 Page, 3 required per study site.

2.2.2 Data collection

The selection of variables to be measured and the techniques used to gather the data from the field were obtained from published studies describing the fire characteristics of forest ecosystems (Table 2). Visual assessments were conducted instead of physically measuring each variable since this approach is quicker for determining a large number of variables in a short amount of time. With the exception of the variable # habitat trees, visual assessments were completed by the same person throughout the 18 study sites. Background information on individual prescribed burns carried out in 2015, including information related to each survey site's topography, weather conditions on the day of the burn, basic fire behaviour and intensity was gathered by pre-burn documentation and through verbal communication in 2014, 2015 and 2016 with Mr Michael Pasotti, Parks and Wildlife Service DBCA Perth Hills District, Fire Coordinator.

2.2.3 Data collection techniques and variables collected

Five pre-fire condition variables including Surface Moisture Content (SMC) and Fire Danger Index (FDI) (Sneeuwjagt & Peet, 1985) were not collected from the field but calculated by the Parks and Wildlife Service, Perth Hills District, Mundaring office for each site prior to the commencement of the burn. SMC is the moisture content expressed as a percentage of oven dry weight of the top 5-10mm of leaf litter and is affected by temperature (°C) and relative humidity (Sneeuwjagt & Peet, 1985). The SMC is estimated for each site, calculated using the Forest Fire Behaviour Tables for Western Australia, 1985. FDI is a relative index of fire danger based on "standard" conditions (McCaw & Burrows, 1989; M Pasotti, 2014 pers com) and was calculated using the forecast of a specific day, including SMC and windspeed (M Pasotti, 2014 pers com; Brain *et al*. 2016). The maximum temperature (°C) and average windspeed (kmh^{-1}) was obtained from the Bureau of Meteorology (BOM) website for each prescribed burn day (Cheney 2012). This data was obtained from the closest weather station to each site. The above four variables, plus month of the burn, were obtained for analysis as they have an influence on fire behaviour (Sneeuwjagt & Peet 1985, Cheney 2012). These five variables plus the twenty-four environmental variables collected from the field make up the total 29 variables surveyed.

The variable time since last burn (TSLB) was also calculated by the Parks and Wildlife Service and was obtained from each study site's prescribed fire plan after the burn was completed. TSLB was analysed as time between burns strongly influences fuel characteristics (McCaw *et* *al*, 2012). TSLB was not included as one of the pre-fire condition variables as it was added at a later date.

A large number of variables have been used in previous studies relating to fire intensity, biodiversity and heterogeneity of landscapes. For each of the 24 variables selected to be measured in the field, the method used to collect it and the importance/what the variable indicates is summarized in Table 2.

Table 2. Details of the environmental variables that were measured in the field surveys, including data collection methods, definition of variables and the importance/what the variables indicate are shown.

Survey Method	**Variable No. and Acronym**	**Post-burn Variable**	**Data collection**	**Definition of Variable**	**Importance/what the variable will indicate**
Transect – 500m	1 (HT)	Habitat trees	Individual trees were counted by visual observation 5 meters each side of each transect line.	A live old tree with a diameter of at least 40 cm at breast height that possesses one or more of the following specific ecological characteristics: gaps in the wood, rotten segments, colonised by fungi, cracks, hollows, and decayed crown compartments or aeries (Bauerle and Nothdurft, 2011).	The quantity and frequency of habitat trees are significant indicators of structural diversity in forest stands (Bauerle and Nothdurft, 2011).
	2 (AB) 3 (VP)	Patch length and number (% burnt and patches km^{-1})	Vegetation cover was measured as the distance of burnt (no vegetation) and unburnt (vegetation) along each line transect. This was estimated using the observer's 1m steps to measure the distance between unburnt and burnt areas.	Presence and absence of vegetation as a distance measure along the transect. Ground burnt - The surface or soil presenting signs of post fire. Signs of post fire include ground that is visibly burnt or charred. Ground cover that was considered under this survey factor, was vegetation and/or leaf litter ≥ 1m. Patch length - Number of burnt patches recorded along the transect.	Patch size and number can affect re-colonisation and local extinction and also provide a measure of the variation in fire behaviour of a hazard- reduction burn (Heemstra, 2007).
Plots – 20 m x 20 m	4 (SLC)	Canopy scorch (%)	Visual assessment to estimate a percentage. This method used 10% intervals ranging from 0% crown scorch to 100% crown scorch.	The browning of leaves within the tree crown as a result of heat from the fire (Cargill, 2014; Alexander and Cruz, 2012).	The mean percentage canopy scorch was obtained for each quadrat. This is an indication of fire intensity (Alexander and Cruz, 2012).

5 (S HGT)	Scorch height (m)	Visually estimated tree height.	The browning of leaves within the tree crown as a result of heat from the fire (Cargill, 2014).	Indicates fire intensity (Alexander and Cruz, 2012).
6 (UB)	Understory burnt (%)	Visual assessment to estimate a percentage of understory area burnt.	Burnt understory was defined as remaining vegetation skeletons; tree or shrub remains ≥ 0.2 m tall (McCaw *et al*. 2012) containing no leaves and visibly charred. If leaves were present, they were scorched.	Indicates patches, potential habitat and burn intensity. Low-moderate intensity fires increase understory production and diversity (Stephens *et al*. 2012)
7 (T HGT)	Tree height (m)	Visual assessment to estimate height.	An average height measurement of the trees within the plot, measured from the ground level to the top. The second observer was used as a height reference.	Provides an indication of forest structure and if trees are tall enough can be used to estimate fire intensity through other variables (e.g. canopy scorch and scorch height)
8 (F HGT)	Flame height (m)	Visual assessment to estimate height.	An average height measurement of the trees within the plot, measured from ground level to the bottom of burnt/charred leaves.	Assists with indicating fire intensity (Alexander and Cruz, 2012).
9 (CB HGT)	Canopy base height (m)	Visual assessment to estimate height.	An average height measurement of the trees within the plot, measured from the ground level to the base of the canopy.	Provides an indication of forest structure and can be used to estimate fire intensity through other variables (e.g. canopy scorch and scorch height)
10 (GB)	Ground burnt (%)	Visual assessment to estimate a percentage of the litter layer burnt.	The surface or soil presenting signs of post fire. Signs of post fire include ground that is visibly burnt or charred. Ground cover that was considered under this survey factor, was vegetation ≤ 0.2m.	Indicates patches within the plot and fire intensity.

11 (BE)	Bare earth (%)	Visual assessment to estimate a percentage.	The ground surface that does not contain a fuel source and thus has not burnt.	Bare earth was a control for dieback disease; high probability of indicating the presence of dieback (Anderson *et al*. 2010)
12 (LC) 13 (LD)	Litter cover (%) and depth (cm)	Percentage of litter cover was completed via visual assessment. Leaf litter depth was only carried out for quadrats containing ≥10% leaf litter. A ruler was vertically inserted until it touched mineral soil in six random locations each containing leaf litter. Measurement was in centimetres, recording from the topsoil to the top of the leaf litter layer. All six measurements were averaged for each plot.	Litter – dead hardwood leaves and woody debris <10 cm in diameter (Franklin *et al*. 1997)	The percentage of litter cover and depth (cm) can determine seedling recruitment and thus overall biodiversity of the forest (Cargill, 2014).
14 (BS HGT)	Bole/bark char height (m)	Bark scorch height (from mineral soil level to the highest point of scorched bark) (Kaufmann and Covington, 2000) was measured using visual assessment. The mean bole char height was calculated and char height variability between species recorded.	The blackening or charring of the outer bark.	Indication of fire intensity and potential post-burn mortality in mature trees (Kaufmann and Covington, 2000).
15 (BCS)	Basal char severity	Calculated using the following categories: 0 = no visible charring of bark; 1 = some blackening around base; 2 = bark plate surface uniformly blackened; 3 = some depth	The blackening or charring of the outer bark at the base of the tree.	This might be important in indicating potential post-burn mortality and/or dieback in mature trees (Kaufmann and Covington, 2000).

		of char; 4 = deep char (Kaufmann and Covington, 2000).		
16 (AC) 17 (WA) 18 (GA) 19 (BA)	Cover and colour of ash (%)	Visual assessment to estimate a percentage.	Three ash colours: White, grey and black.	White ash - indicates fallen woody debris consumed by fire. Grey ash - the product of complete combustion. Black ash (char) - the product of incomplete combustion. (Hudak *et al*. 2013). This gives an indication of fire intensities across the burn and assists in determining patches.
20 (BT)	Fire Intensity (Branch Thickness (mm))	Visual assessment to assign a category.	Small branches - < 25 mm diameter Large branches - > 25 mm diameter (McCaw, 2011) Fire intensity will be further referred to as Branch thickness (mm).	Gives an indication of fire intensity. Small branches = low intensity burn. Large branches = high intensity burn (McCaw, 2011).
21 (CC)	Canopy cover (%)	Visual assessment to estimate a percentage.	Green leaves in the canopy, burnt or scorched leaves are excluded.	Indicates patches within the plot and fire intensity.
22 (GVC)	Ground vegetation cover (%)	Visual assessment to estimate a percentage.	Ground cover that was considered was vegetation $\leq$ 0.2m.	Indicates patches within the plot and fire intensity.
23 (SC)	Shrub cover (%)	Visual assessment to estimate a percentage.	Understory of shrubs, 0.2 to 3 m tall (McCaw *et al*. 2012)	Indicates patches within the plot and fire intensity.
24 (OE)	Orange earth cover (%)	Visual assessment to estimate a percentage.	Orange soil at the ground surface	Presence and quantity indicates high soil burn severity (Parsons *et al*, 2010)

2.3 Data analysis to determine patchiness creating variables

2.3.1 Pearson correlation analysis – Matrix table

A total of 29 environmental variables were measured for each prescribed burn, twenty-four collected via field surveys and five pre-fire condition variables. A Pearson correlation analysis matrix table was constructed (See section 2.3.4 Elimination of covaring variables) to determine the significant correlations between variables as well as the strength of the relationships (coefficient of determination, r^2) (Table 2). Significant correlations between variables are shown in the matrix table and these were further explored. In particular I examined:

- General significant correlations and trends that appeared in the Pearson correlation matrix,
- The relationship between pre-fire condition variables (FDI, SMC, windspeed and temperature) and fire intensity variables,
- Fire intensity variables and how they related to the number of vegetation patches and burnt area, and
- The relationship of post-fire vegetation variables with the number of vegetation patches and area burnt.

SPSS (Version 23) was used to determine the P-value or significance ($P \leq 0.05$) of the correlations as well as the coefficient of determination, r^2 which is displayed on each scatter graph (graphs were created using Microsoft Excel) along with the trendline and equation of only significant relationships.

2.3.2 Season of burn

SPSS (Version 23) was also used to undertake a 2 tailed t-test to compare the total number and mean length of post-burn patches between autumn and spring prescribed burn sites. The mean patch length and mean number of patches (# km^{-1}) was calculated for burns undertaken in spring (n = 11) and autumn (n = 7). A bar graph was created using Microsoft Excel to compare the mean patch length and number of patches within the two seasons, spring and autumn. The standard deviation errors bars are presented on the bar graph. The frequency distribution of vegetation patch lengths was graphed using 10 m size classes for each of the 18 prescribed burn sites (using Microsoft Excel). Autumn and spring burns are graphed separately for comparison.

2.3.3 Time since last burn, # veg patches and fire intensity

The relationship between time since last burn and the number of vegetation patches (# km^{-1}) and fire intensity was determined. Fire intensity variables that significantly correlated ($P \leq 0.05$) with time since last burn were graphed as well as the variables # veg patches and SMC. The p-value and coefficient of determination, r^2 were determined in SPSS, with the r^2 being presented alongside the trendline and equation on the scatter graphs.

2.3.4 Elimination of covaring variables

Three out of the 29 variables collected were deemed unreliable due to environmental influences impacting on the reliability of the collection of the variable and were thus removed from the data set before analyses were undertaken. These included white ash cover (%), grey ash cover (%) and black ash cover (%). The remaining data collected from the field was analysed through Generalised Linear Modelling (GLM) using SPSS. The GLM analysis requires a reduced number of variables since there were only 18 survey sites in total. To do this all variables with strong correlations were examined and a single variable selected as a surrogate for all the covaring variables for use in the GLM analysis. After this process had been completed there was a final data set of 11 variables, including the dependent variable (#Veg Patches), that were used. The 11 variables included: #Veg Patches, FDI: Fire Danger Index, SMC: Surface Moisture Content, WS: Windspeed (km/h), AC: Ash cover (%), AB: Area burnt (%), BCS: Basal char severity (Categorical), F Hgt: Flame height (m), MF: Month of fire (Categorical), HT: Habitat trees (#), MT: Max temperature (°C).

2.3.5 Development of candidate models

The 11 variables in the final data set were put through a GLM analysis using Statistica 7 with the number of vegetation patches as the dependant variable. The GLM analysis produced a list of best subset models and the Akaike Information Criterion (AIC) corrected for small sample size (AICc) was used to select the most parsimonious models. The most parsimonious model will contain the variables that are important for the creation of patchiness.

2.3.6 Assessment of the quality of models

Akaike's information criterion (AIC) was used to select the most parsimonious models from a set of candidate models. The second order Akaike Information Criterion (AICc) is used when the sample size (n) is less than 40 times the number of parameters (k) (Anderson *et al*. 2001;

Burnham & Anderson, 2004; Johnson & Omland 2004). The formula for calculating AICc is as follows:

$$\boxed{\mathrm{AIC}_c = -\, 2\log_e(\mathrm{L}(\hat{\theta})) + 2\mathrm{K} + \frac{2K(K+1)}{(n-K-1)}}$$ (Burnham & Anderson, 2001)

The AICc indicates which models are most parsimonious or plausible candidate models (AICc < 2). The model with the lowest AICc or AIC is considered the 'best' model out of the candidate models and the best at explaining the observed data (Mazerolle, 2004; Johnson & Omland, 2004).

To compare the models, delta AICc (Δ_i) and Akaike weights (w_i) were both calculated, providing a measure of the strength of evidence for each model (Mazerolle, 2004). The delta AICc (Δ_i) is the difference between a model's AICc and the AICc of the most parsimonious model (Mazerolle, 2004; Westphal *et al*. 2003). The Δ_i is calculated due to model selection uncertainty (Johnson & Omland, 2004). This refers to the idea that merely choosing the model with the lowest AICc is not adequate since other models can potentially have an AICc close to the lowest AICc with few variables and can therefore be considered equally parsimonious (Johnson & Omland, 2004). The Δ_i shows the exact difference for assessment. Models with a $\Delta_i \leq 2$ are said to be equally likely as the model with the lowest AICc (Westphal *et al*. 2003, Burnham & Anderson, 2004). Models with an Δ_i of ≤ 4 and ≤ 7 suggests less support for the model, and Δ_i of > 10 indicates that the model is improbable (Burnham & Anderson, 2003; Burnham & Anderson, 2004). Δ_i is calculated via the following formula:

$$\boxed{\Delta_i = \mathrm{AIC}_i - \mathrm{minAIC}.}$$ (Burnham & Anderson, 2001)

AICi = AIC value for model i, and min AIC = AIC value from the 'best' model (most parsimonious model) (Mazerolle, 2003). The calculation for determining the delta AIC does not change weather the AIC or AICc is used (Mazerolle, 2004). For this thesis, the delta AIC (Δ_i) was calculated using the AICc, and is thus the difference between a model's AICc and the AICc of the most parsimonious model.

Akaike Weights (w_i) were calculated and indicate the probability of a model being the 'best' out of a set of models (Westphal *et al*. 2003; Mazerolle, 2004; Johnson & Omland, 2004). The

w_i is the ratio of Δ_i values for each model comparative to the set of R models being considered (Westphal *et al*. 2003; Mazerolle, 2004). The formula to calculate Akaike Weights (w_i) is as follows:

$$w_i = \frac{\exp(-\Delta_i / 2)}{\sum_{r=1}^{R} \exp(-\Delta_r / 2)}$$

(Burnham & Anderson, 2001)

The w_i shows (as a percentage) the probability of the model being the 'best' model. For example, if a model has an Akaike weight of 0.68, this indicates that the model is 68% likely of being the 'best' model out if the set of candidate models (Mazerolle, 2004).

2.3.7 Variable contribution - Structured Equation Modelling and path diagram.

Structured Equation Modelling (SEM) was undertaken in IBM Amos to see which variables in the 'most parsimonious' or 'best' model were the greatest contributors to the model. The P-Values in the Covariance table indicated significant correlations ($P \leq 0.05$) between independent variables and the least informative were removed from the data set and thus the final model. Standardized Regression Weights table indicate significant correlations ($P \leq 0.05$) between independent variables and the dependent variable. Independent variables that are significantly correlated with the dependent variable are the 'divers' of the model and have a strong influence on the dependent variable. The final variables that make up the 'best' model for predicting patchiness are presented in a Path Diagram (Fig 18), showing the significance of each variable within the model and the variable correlations together with an overall Coefficient of Variation (r^2 – value).

2.4 Comparison of current DBCA post-burn survey data with the patchiness survey

The results of each post-burn assessment conducted by Parks and Wildlife Service were obtained for each of the 18 prescribed burn sites tested in this study. These results were compared to the post-fire patchiness survey data obtained in this study for the same 18 post fire sites. The post-burn evaluation conducted by the Parks and Wildlife Service consist of a series of Yes/No/Partially answer in relation to the success criteria stated in the prescribed fire plan for each site. Each prescribed burn has its own fire plan and set of success criteria which means that sites do not have the same success criteria. Where a success criteria was not listed as a criteria for a particular site, it is noted with a '–' symbol.

Four variables from the post-fire surveys (# veg patches (# km^{-1}), area burnt (%), scorch height (m) and scorched leaves (%)), were used to compare with the Parks and Wildlife post-burn assessments as these variables were the most informative variables, out of the 29 variables surveyed, to represent the success criteria shown in the Parks and Wildlife Service survey. The mean and standard deviation of each of the four variables was calculated for each site.

Results

Post-fire surveys were completed between the months of June 2015 and February 2016. Time between the execution of the prescribed burn and the survey varied from 34 days up to 138 days.

3.1 Identifying significant correlations between variables and strength of relationships - Pearson correlation analysis

Pearson correlation analysis showed that the majority of the significantly correlated post-fire variables were those collected along transects and within the quadrats with few correlations seen with pre-fire conditions (Table 3). Variables such as tree height (m) and canopy base height (m) which are not direct indicators of fire intensity, or patchiness, showed very few correlations with other variables. The number of vegetation patches (# km^{-1}) variable had a large number of significant correlations with other post-fire variables with most of these being negative correlations (Table 3).

Pearson correlation results showed that several variables that are known to be indicators of fire intensity, including #veg patches (# km^{-1}), area burnt (%), scorch height (m), scorched leaves (%), flame height (m) and bark scorch height (m), were all correlated with a large number of variables. The variables scorched leaves (%) and flame height (m) showed a significant ($p \leq 0.05$) positive correlation with an R^2 of 0.523. Scorched leaves (%) and bark scorch height (m) showed a weaker but still significant ($p \leq 0.05$) correlation, with an R^2 value of 0.420. Scorch height (m) and bark scorch height (m) were strongly correlated with an R^2 value of 0.731 which is not unexpected.

Table 3. Pearson's Correlation analysis of 21 post-fire variables collected in field surveys (n = 51), and 5 pre-fire condition variables collected from prescribed fires (n = 18) in the northern Jarrah forest. Significantly ($p \leq 0.05$) correlated variables are highlighted in grey. Transect variables shown in italics. Quadrat variables shown in bold text. Pre-fire condition variables shown as normal text.

Variable	***#VP***	***AB (%)***	**T HGT (m)**	**S HGT (m)**	**SLC (%)**	**F HGT (m)**	**CB HGT (m)**	**BS HGT (m)**	**CC (%)**	**UB (%)**	**GB (%)**	**GVC (%)**	**SC (%)**	**BE (%)**	**LC (%)**	**LD (cm)**	**BCS**	**AC (%)**
#VP	1.00																	
AB (%)	-0.72	1.00																
T HGT (m)	-0.26	0.29	1.00															
S HGT (m)	-0.34	0.34	0.50	1.00														
SLC (%)	-0.47	0.28	-0.08	0.44	1.00													
F HGT (m)	-0.42	0.24	0.09	0.33	0.63	1.00												
CB HGT (m)	-0.26	0.32	0.97	0.57	-0.07	0.05	1.00											
BS HGT (m)	-0.49	0.40	0.56	0.69	0.61	0.66	0.54	1.00										
CC (%)	0.18	-0.22	0.15	-0.35	-0.61	-0.37	0.11	-0.40	1.00									
UB (%)	-0.64	0.63	0.14	0.46	0.50	0.33	0.23	0.47	-0.44	1.00								
GB (%)	-0.44	0.51	0.12	0.24	-0.03	-0.14	0.21	0.10	-0.00	0.63	1.00							
GVC (%)	0.44	-0.49	0.02	-0.32	-0.30	-0.20	-0.05	-0.29	0.48	-0.72	-0.63	1.00						
SC (%)	0.61	-0.58	-0.17	-0.37	-0.33	-0.22	-0.23	-0.36	0.24	-0.82	-0.66	0.76	1.00					
BE (%)	-0.09	-0.04	-0.03	0.06	0.46	0.48	-0.10	0.29	-0.43	0.02	-0.70	0.10	0.07	1.00				
LC (%)	0.57	-0.63	-0.05	-0.43	-0.50	-0.30	-0.12	-0.40	0.55	-0.86	-0.62	0.85	0.72	-0.00	1.00			
LD (cm)	0.67	-0.56	-0.07	-0.39	-0.50	-0.32	-0.09	-0.46	0.55	-0.80	-0.54	0.70	0.74	-0.13	0.81	1.00		
BCS	-0.34	0.15	0.04	0.24	0.32	0.34	0.06	0.33	-0.20	0.48	0.39	-0.37	-0.47	-0.07	-0.38	-0.44	1.00	
AC (%)	-0.27	0.15	-0.15	-0.02	0.28	0.36	-0.20	0.18	0.14	0.19	0.19	-0.18	-0.24	-0.07	-0.11	-0.13	0.32	1.00
OE (%)	-0.27	0.17	0.22	0.14	0.13	0.31	0.22	0.29	-0.08	0.18	0.02	-0.28	-0.32	0.21	-0.15	-0.18	0.27	0.37
BT (mm)	-0.28	0.23	0.07	0.17	0.34	0.65	-0.01	0.36	-0.21	0.22	-0.10	-0.12	-0.20	0.37	-0.20	-0.20	0.32	0.24
MF	0.12	-0.00	-0.44	-0.06	-0.02	-0.22	-0.35	-0.31	-0.24	0.05	0.26	-0.26	-0.03	-0.23	-0.26	-0.15	-0.12	-0.27
FDI	0.11	-0.23	-0.03	-0.14	-0.02	-0.03	-0.08	-0.02	-0.06	-0.14	-0.31	0.15	0.16	0.33	0.25	0.06	-0.23	0.01
SMC	0.24	0.07	0.03	-0.12	-0.34	-0.31	0.05	-0.24	0.35	-0.01	0.15	0.06	-0.01	-0.28	0.02	0.22	0.04	-0.10
MT (°C)	-0.14	0.00	-0.16	-0.01	0.24	0.12	-0.18	0.07	-0.22	0.04	0.06	-0.17	-0.06	0.07	-0.13	-0.25	-0.02	0.15
WS (km/h)	0.20	-0.22	0.09	-0.22	-0.18	-0.16	0.03	-0.07	0.12	-0.18	-0.32	0.27	0.15	0.28	0.41	0.19	-0.22	0.03
#HT	0.24	0.02	0.08	0.04	-0.38	-0.17	0.08	-0.04	0.40	-0.15	0.18	-0.08	0.04	-0.41	0.11	0.23	-0.05	0.30

Table 3 (cont'd). Continued Pearson's Correlation analysis

Variable	OE (%)	BT (mm)	MF	FDI	SMC	MT (°C)	WS (km/h)	*#HT*
OE (%)	1.00							
BT (mm)	0.02	1.00						
MF	-0.27	-0.37	1.00					
FDI	-0.07	-0.09	-0.06	1.00				
SMC	0.07	-0.08	-0.08	-0.56	1.00			
MT (°C)	-0.13	-0.09	0.30	0.52	-0.59	1.00		
WS (km/h)	0.14	-0.18	-0.32	0.82	-0.17	0.20	1.00	
#HT	0.08	-0.11	-0.05	-0.22	0.46	-0.16	-0.09	1.00

The relationship between area burnt (%) and # veg patches (# km^{-1}) showed a statistically significant ($p \leq 0.05$) negative correlation, with a R^2 value of 0.540 showing that as the area of vegetation burnt decreased there was a corresponding increase in the number of vegetation patches km^{-1} (Fig 6).

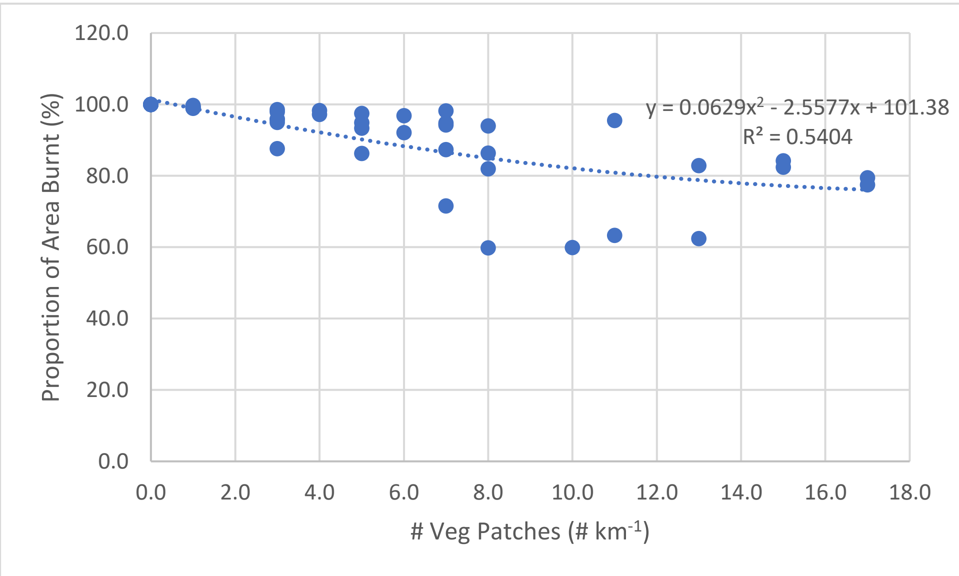


Figure 6. Relationship between the proportion of area burnt (%) and number of vegetation patches (# km^{-1}) resulting from prescribed fires in the northern Jarrah forest.

As one would expect, where 100% of the area was burnt there were no patches recorded. However, the converse did not apply since the existence of a high number of vegetation patches did not necessarily mean that less area was burnt since the remaining patches ranged in length. For example, where 17 patches were recorded, the area burnt was still up around 80% (Fig 6). The survey template sites where the area burnt was less than 70% had an intermediate number of patches (8 to 10 km^{-1}) which are presumably larger than those recorded at the template sites with more patches (Fig 6).

A large percentage of the 51 survey templates had over 90% area burnt (Fig 6). Over the 18 post-burn survey sites, 17 had an average of 80% area burnt, while 11 sites had over 90%. One survey site had 100% area burnt, while another had 79.6%, this being the lowest percentage of area burnt over the 18 sites.

Scorch height (m) which is often used as an indication of fire intensity showed a significant ($p \leq 0.05$) correlation with the number of vegetation patches ($R^2 = 0.271$). Since this is a weakly negative correlation the decrease in scorch height (i.e. a decrease in fire intensity) results in a greater number of patches (Fig 7a). The variables branch thickness (mm) and number of veg patches (# km^{-1}) showed a weak but significant ($p \leq 0.05$) negative correlation with an R^2 of 0.119. Branch thickness is also often used as an indication of fire intensity and the negative correlation showed that areas with zero or few vegetation patches have slightly higher branch thickness remaining (Fig 7b) which is indicative of high fire intensities.

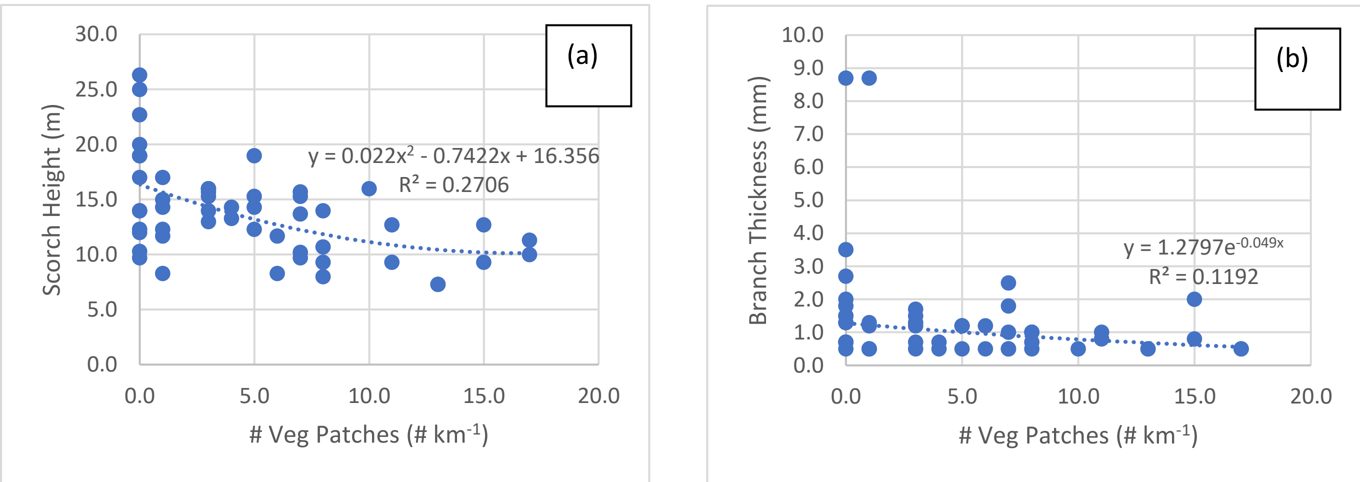


Figure 7. Relationship between (a) scorch height (m) and (b) branch thickness (mm) and the number of vegetation patches (# km^{-1}) resulting from prescribed fires in the northern Jarrah forest.

The significant ($p \leq 0.05$) positive correlation between remaining litter cover (%) and number of patches showed that there was generally more litter cover with an increase in the number of vegetation patches (Fig 8). The weak correlation (R^2=0.334) also showed that some areas had a high number of vegetation patches (# km^{-1}) with no litter cover. It would appear that in this case the correlations between variables measured via different methods (transect or quadrat) were influenced by the method of collection (Fig 8). Quadrats which are limited in area covered tend to reflect local fire conditions and those that had experienced a high intensity burn often showed zero litter cover. In contrast the greater area covered in counting patches along a transect, in the same survey area, showed a large number of vegetation patches.

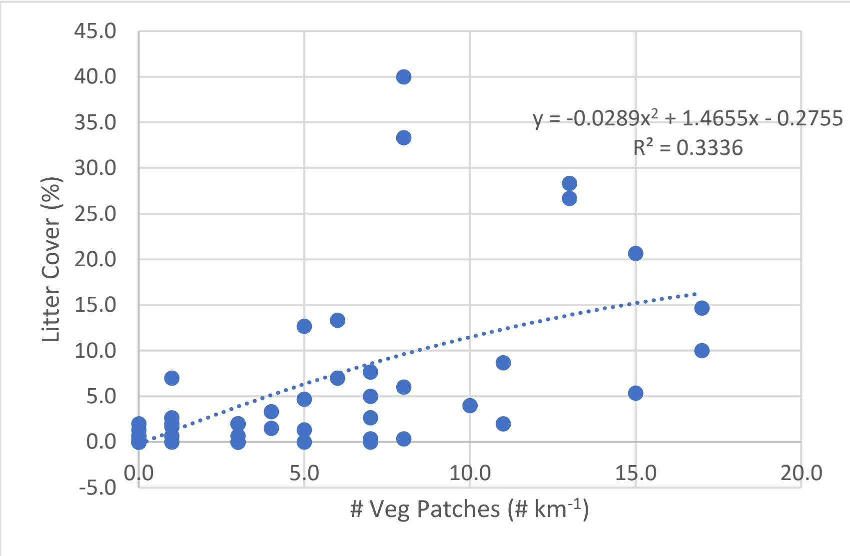


Figure 8. Relationship between litter cover (%) and the number of vegetation patches (# km^{-1}) resulting from prescribed fires in the northern Jarrah forest.

3.2 Pre-fire condition variables and fire intensity

Flame height (m), scorched leaves (%) and canopy cover (%) are known indicators of fire intensity. Variables flame height (m) and scorched leaves (%) showed statistically significant ($p \leq 0.05$) negative correlations with Surface Moisture Content while flame height (m) and SMC had a weak correlation with an R^2 of 0.268 (Fig 9a), scorched leaves (%) had a similarly weak correlation (R^2 = 0.235) (Fig 9b). The negative correlations showed the expected relationship that fire intensities were lower when the SMC values increased.

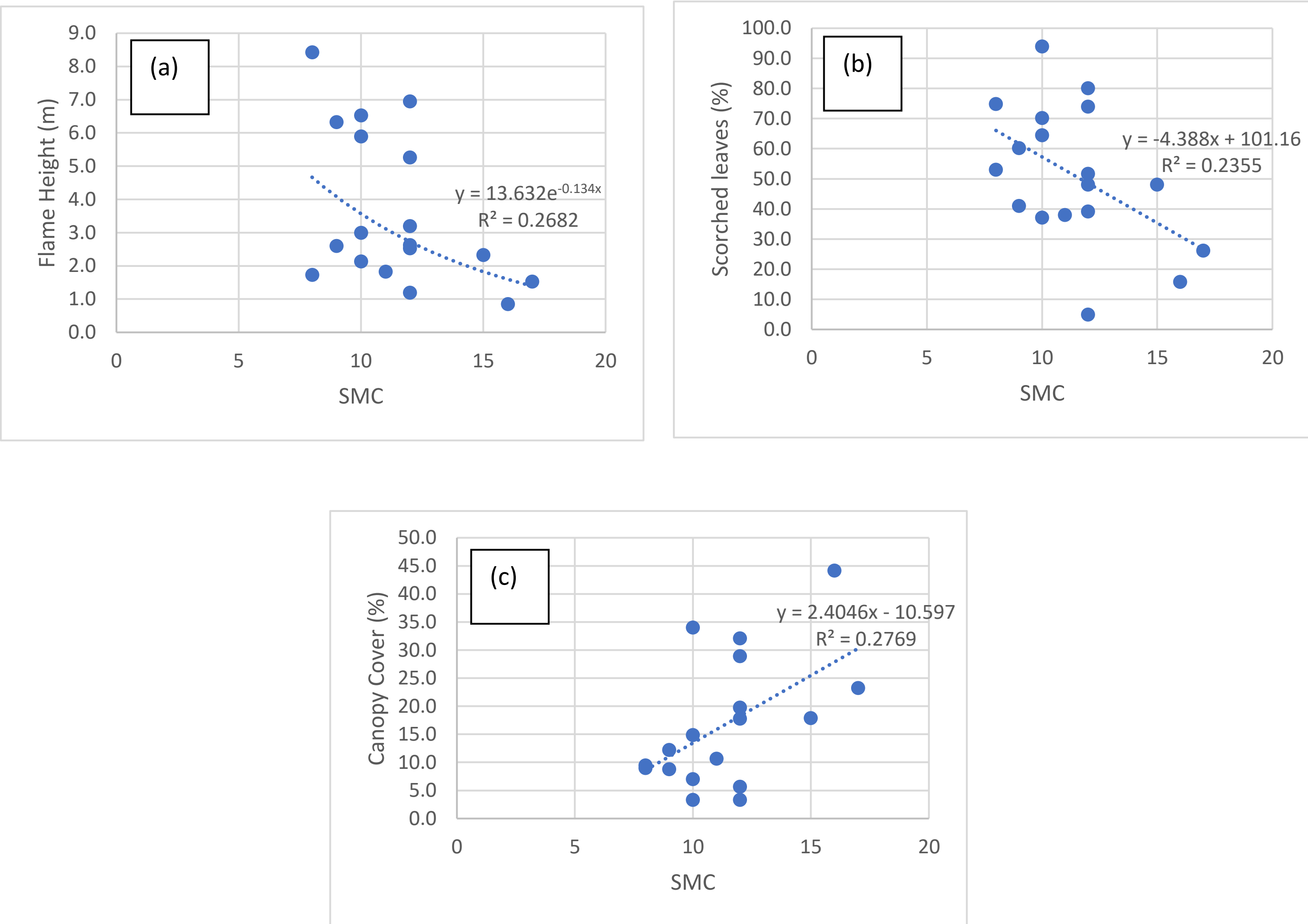


Figure 9. Relationship between (a) flame height (m), (b) scorched leaves (%), and (c) canopy cover (%) and the pre-fire condition variable Surface Moisture Content calculated prior to prescribed fires in the northern Jarrah forest.

Canopy cover (%) and SMC also showed a significant ($p \leq 0.05$) positive correlation with an R^2 of 0.277 showing that canopy cover increases with an increase in SMC (i.e. fire intensity decreases with an increase in SMC) (Fig 9c). The pre-fire condition variables max temp (°C), month of fire, FDI and windspeed (km/h^{-1}) were not significantly correlated with fire intensity variables which might be because these variables are constrained because of the selection of similar weather conditions on all days selected for the prescribed burns.

3.3 Fire intensity variables related to the number of patches and area burnt

Scorched leaves (%) showed a significant ($p \leq 0.05$) negative correlation with the number of vegetation patches km^{-1} ($R^2 = 0.220$) (Fig 10a). Similarly, the variable flame height (m) also showed a weak but significant ($p \leq 0.05$) negative correlation with # veg patches ($R^2 = 0.252$) (Fig 10c). Since both are negatively correlated and are known indicators of fire intensity, the increase in percentage of scorched leaves within the canopy, and the height of the flames resulted in a decline in number of vegetation patches, which was expected. The relationship between scorched leaves (%) and area burnt (%) showed a statistically significant ($p \leq 0.05$) positive correlation, with a low R^2 value of 0.115 (Fig 10b). Scorched leaves (%) was also weakly correlated with the percentage of area burnt suggesting that as fire intensity increased so there was an increase in the percentage of area burnt (Fig 10b) with 90% to 100% of the area burnt in the 51 surveys at the 18 sites.

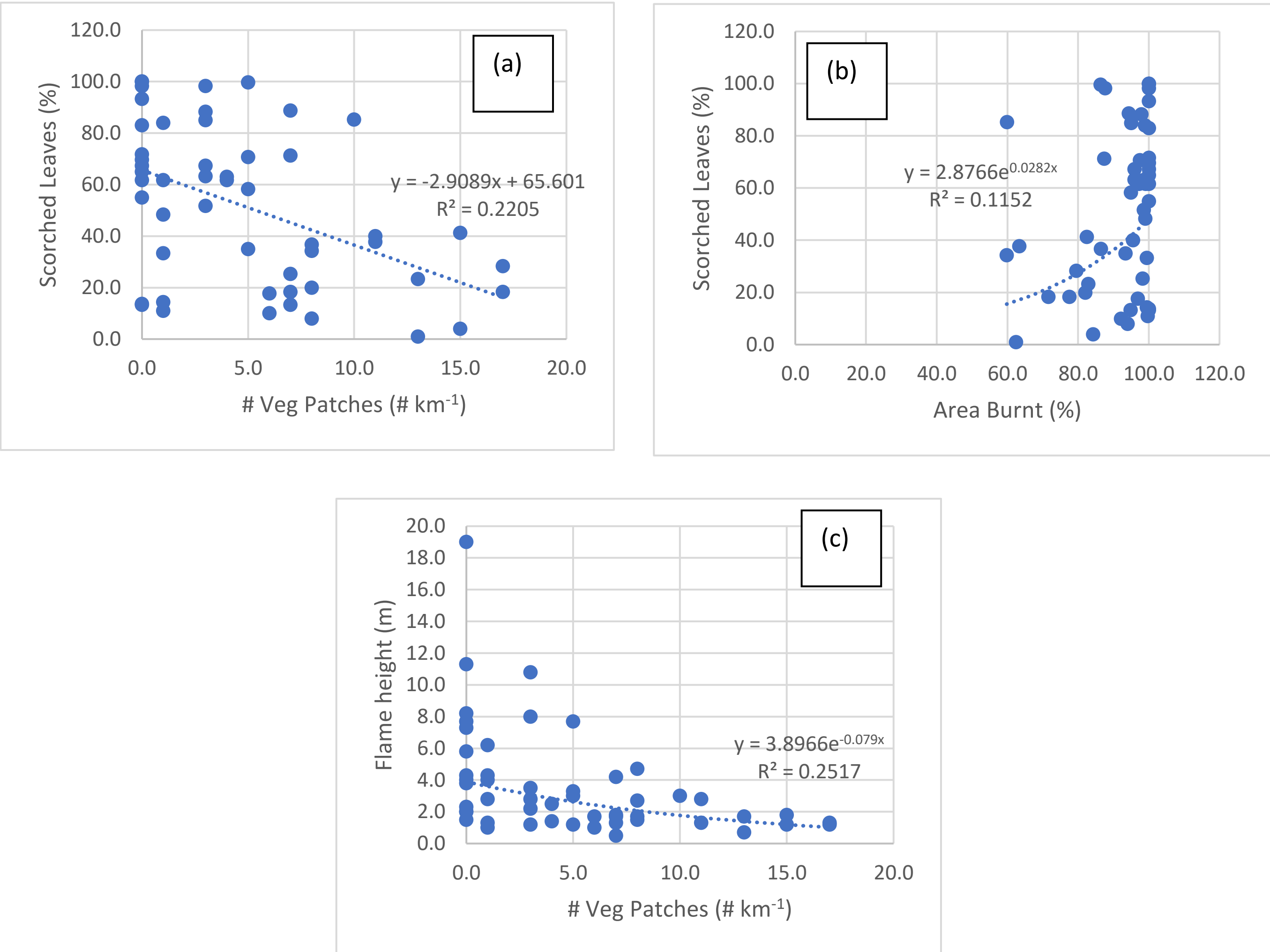


Figure 10. Relationship between (a) scorched leaves (%) and # veg patches (# km^{-1}), (b) scorched leaves and area burnt (%), and (c) flame height (m) and # veg patches (# km^{-1}), resulting from prescribed fires in the northern Jarrah forest.

Pre-fire condition variables FDI and SMC, as well as canopy cover (%), were not significantly correlated with the number of patches nor with the percentage of area burnt. Variables flame height (m) and scorched leaves (%) were both significantly ($p \leq 0.05$) correlated with pre-fire condition variable SMC (Fig 9a, 9b) as well as vegetation patches (Fig 10a, 10c). This indicated that Surface Moisture Content is the only pre-fire condition variable that was shown to influence fire intensity and subsequently the number of vegetation patches (# km^{-1}) in this study.

3.4 Relationship of post-fire vegetation variables with the number of patches and area burnt

Shrub cover (%), ground veg cover (%) and litter depth (cm) showed significant ($p \leq 0.05$) positive correlations with the number of vegetation patches. Shrub cover (%) and # veg patches (# km^{-1}) were weakly correlated with an $R^2 = 0.382$ (Fig 11a). The variables ground veg cover (%) and # veg patches (# km^{-1}) were also weakly correlated ($R^2 = 0.215$) (Fig 11c), while litter depth (cm) and #veg patches (# km^{-1}) was the strongest with $R^2 = 0.488$ (Fig 11e). Increased percentages of shrub cover, ground vegetation cover and litter depth all resulted in an increased number of vegetation patches which was expected since these variables all relate to the amount of vegetation remaining after the fire. The area burnt (%) was high within sites, with the majority of the sites having between 90 to 100% burnt, with less than 5 % shrub cover (Fig 11b) and ground veg cover remaining (Fig 11d). The area burnt (%) showed a significant ($p \leq 0.05$) weak negative correlation with the variables shrub cover (%), ground vegetation cover (%) and litter depth (cm) with R^2 values ranging from 0.343 to 0.441 (Fig 11b, d, f). There was a strong similarity in overall pattern shrub cover (%), ground vegetation cover (%) and litter depth (cm) all decreasing as the area burnt increased which again is not surprising since these variables all indicate vegetation remaining after the fire.

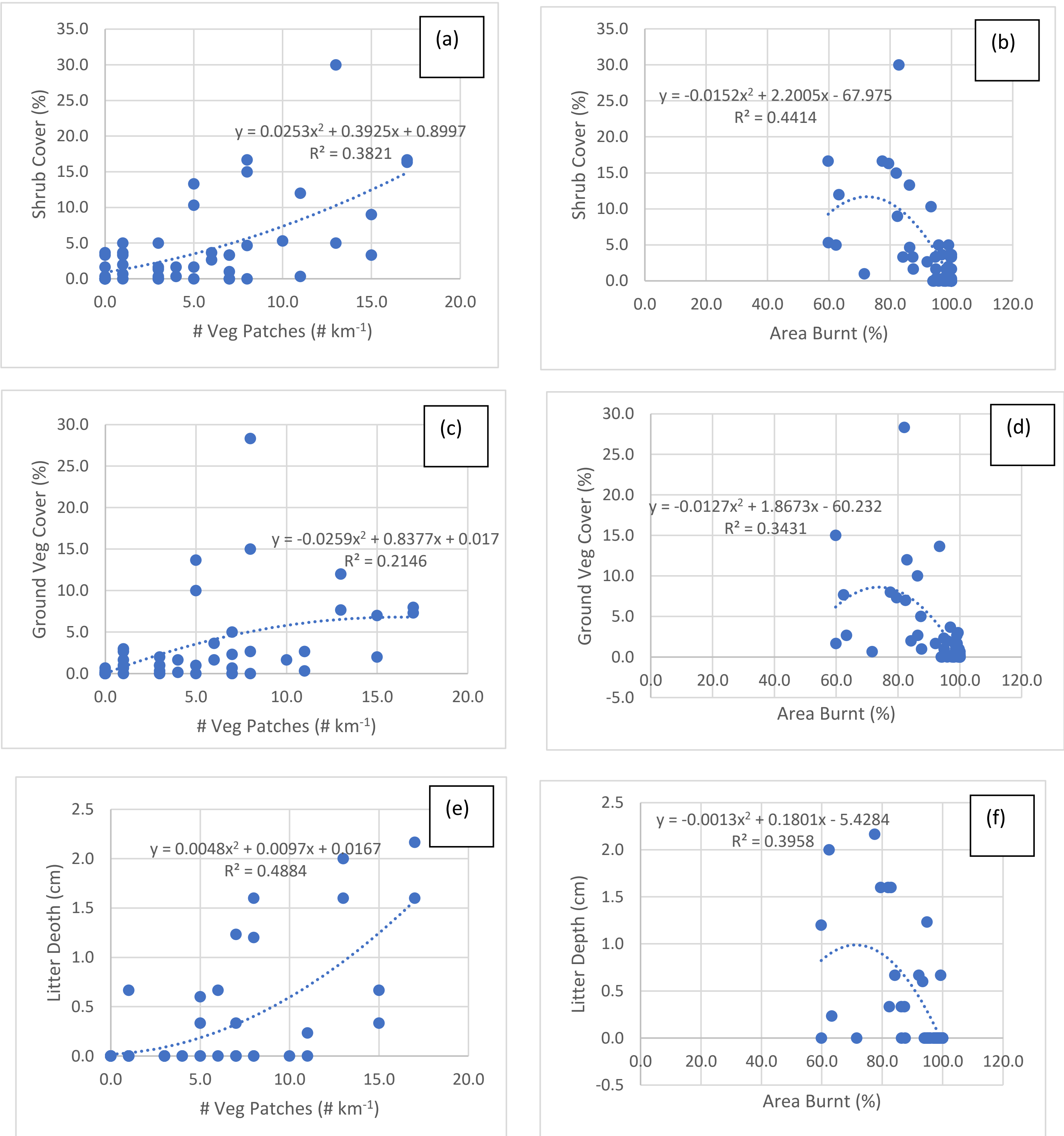


Figure 11. Relationship between (a) shrub cover (%) and # veg patches (# km^{-1}), (b) shrub cover (%) and area burnt (%), (c) ground veg cover (%) and # Veg Patches (# km^{-1}), (d) ground veg cover (%) and area burnt (%), (e) litter depth (cm) and # veg patches (# km^{-1}), and (f) litter depth (cm) and area burnt (%), resulting from prescribed fires in the northern Jarrah forest.

3.5 Season and its impact on patchiness

The mean patch length was higher, and presented more variability, in autumn post burn sites than in spring burns (Fig 12). In addition, the mean number of patches (# km^{-1}) was shown to be higher in spring burns than in autumn, although autumn burns presented greater variability over spring. This indicates that autumn burns present greater variability in vegetation patch length and number over spring burn sites, with spring producing patches that are more similar in length and number over the sites. The results show that the mean number of patches km^{-1} is less than 16, with an average length of less than 18 m, at both autumn and spring burn sites which is considered small. The standard deviation errors bars overlap quite a bit over the four means, indicating that the difference is not statistically significant between the mean patch length (m) and mean total number of patches km^{-1} in autumn and spring burns (Fig 12).

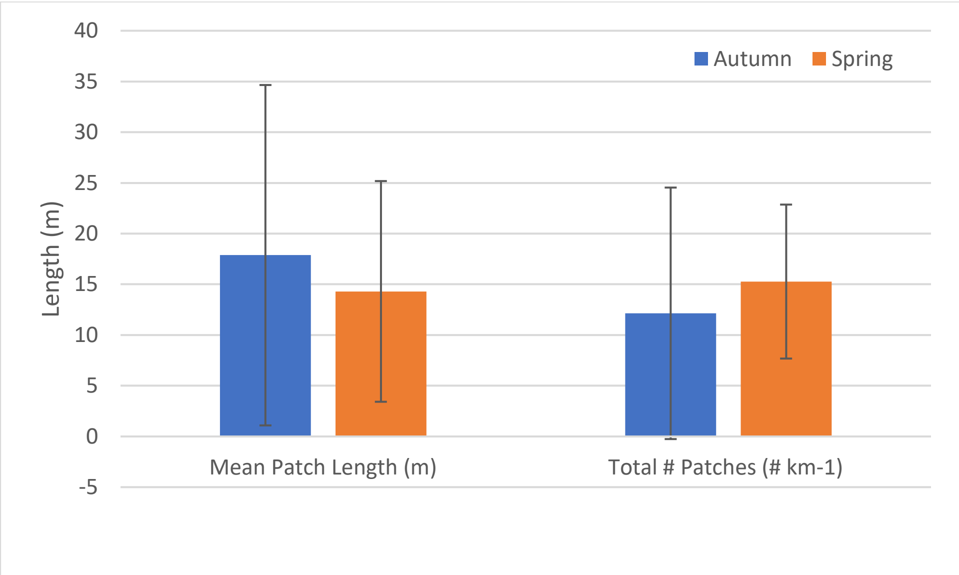


Figure 12. The mean (± SD) vegetation patch length (m) and mean (± SD) number of patches (# km^{-1}) within autumn (n=7) and spring (n=11) prescribed burn sites.

A 2-tailed t-test showed that there is no difference in the mean patch lengths between autumn and spring post-burn sites (t= 0.55, df = 16, p = 0.589). The total number of vegetation patches (# km^{-1}) at autumn post-burn sites are not significantly different to the number of patches (# km^{-1}) at the spring sites (t = 0.669, df = 16, p = 0.513). This shows that there is no significant difference between spring and autumn burns in relation to the mean patch lengths and total number of patches # km^{-1} post-burn.

The relationship shown earlier between the # veg patches km^{-1} and area burnt (%) (Fig 6) indicated that areas with a large number of veg patches also have a large percentage of area burnt. A high percentage of vegetation patches in both autumn (Fig 13) and spring (Fig 14) burns are shown to be small, between 1 – 10 m in length.

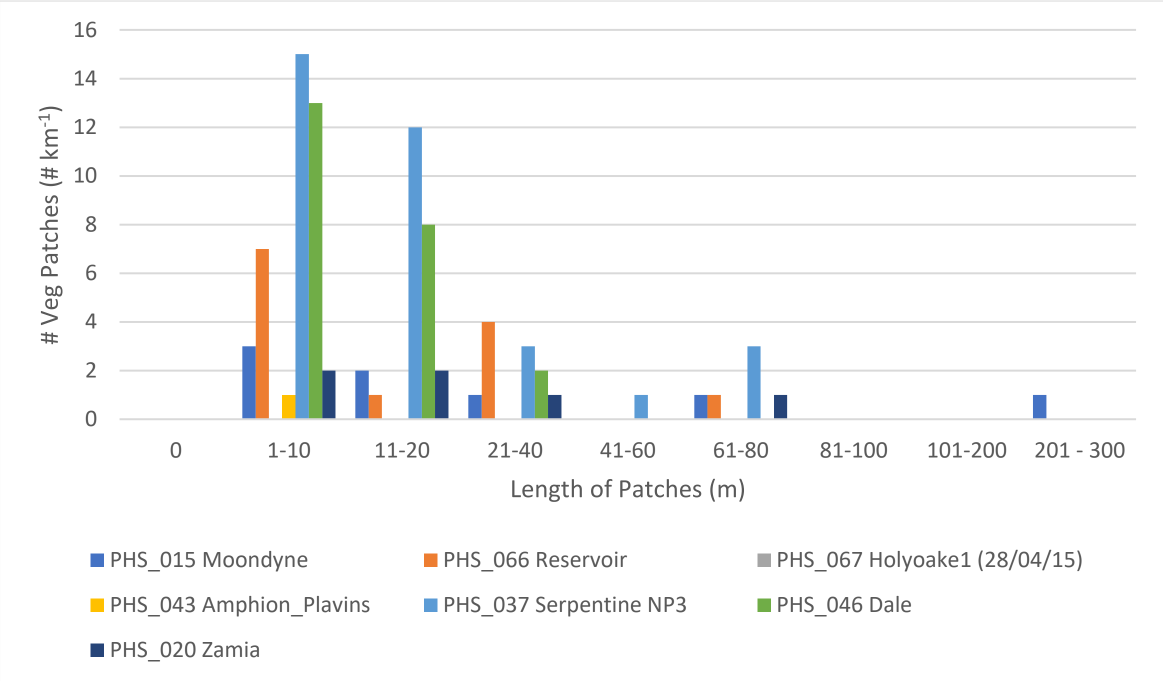


Figure 13. Shows the length and number of patches km^{-1} at each of the 7 sites surveyed in autumn. Where a site has zero patches, the corresponding colour to the site name will not appear on the graph.

Forty eight percent of patches identified within post-autumn prescribed burn survey sites fall between 1 -10 m in length, followed by patches 11-20 m in length at 29% (Fig 13). The site with the largest number of patches was PHS_037 Serpentine NP3 with 34 patches ranging in length. Fifteen of the 34 patches fell between 1-10 m in length. The largest patch overall was at PHS_015 Moondyne and was between 201m to 300m. PHS_015 Moondyne also presented a number of smaller patches across the scale. The survey site PHS_043 Amphion_Plavins presented one patch, 1 – 10 m in length, and PHS_067 Holyoake1 (28/04/15) had zero patches (Fig 13).

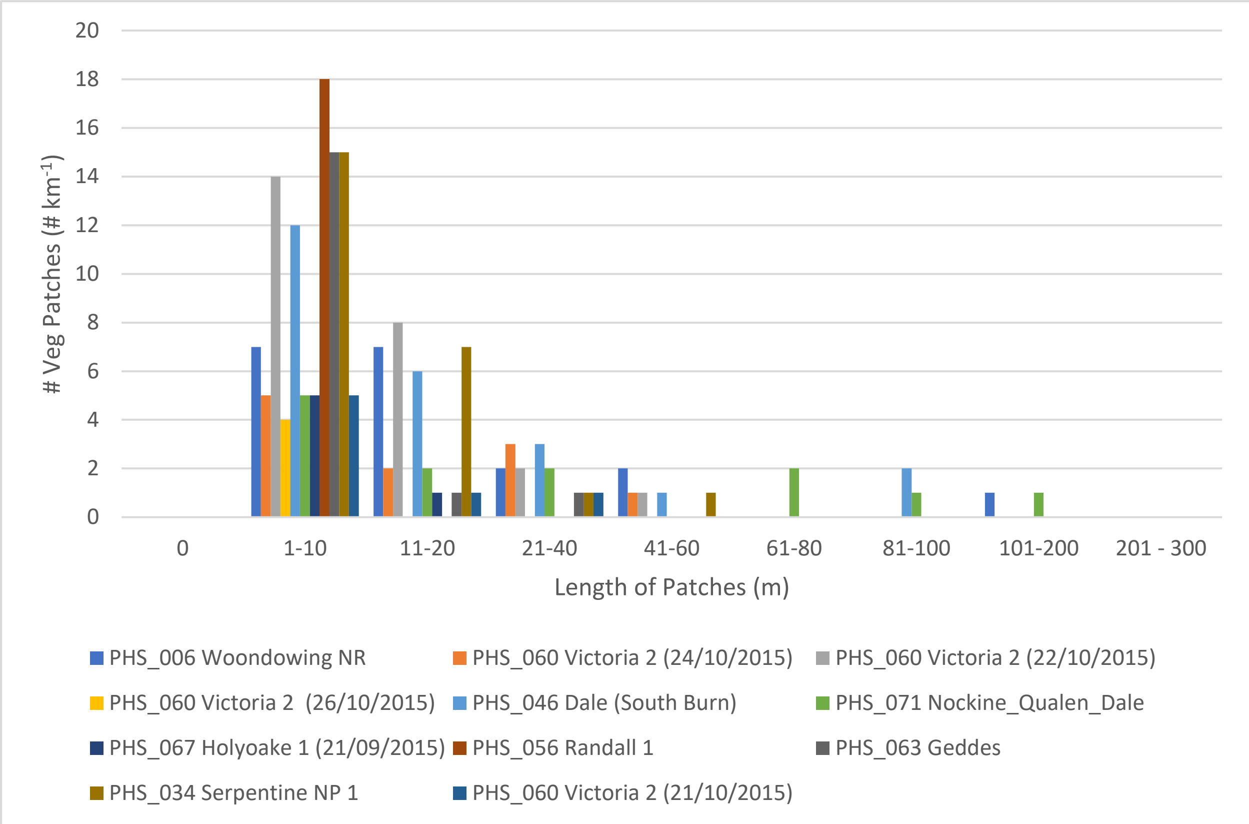


Figure 14. Shows the length and number of patches km^{-1} at each of the 11 sites surveyed in spring. Where a site has zero patches, the corresponding colour to the site name will not appear on the graph.

The survey site PHS_046 Dale (South Burn) had 24 patches with 50% between 1-10 m in length (Fig 14). Although PHS_046 Dale (South Burn) had the largest number of patches for spring post burn sites, PHS_060 Victoria 2 (26/10/2015) had the lowest number of patches with 4 km^{-1} patches recorded, all 1-10 m in length. The largest spring patches were between 101 – 200m in length. Six of the 11 spring survey sites presented patches in at least 4 different length categories, however spring burns are consistent with autumn burns and 62% of patches fall within the 1 – 10 m length category (Fig 14).

3.6 Relationship between time since last burn, # veg patches and fire intensity.

Time since last burn (TSLB) (yrs) showed a significant ($p \leq 0.05$) positive correlation with the variable # veg patches ($R^2 = 0.526$) (Fig 15). The positive correlation showed that within spring burns, the number of vegetation patches increases with time since last burn. The variables #veg patches (# km^{-1}) and TSLB (yrs) were not significantly correlated for burns undertaken in autumn.

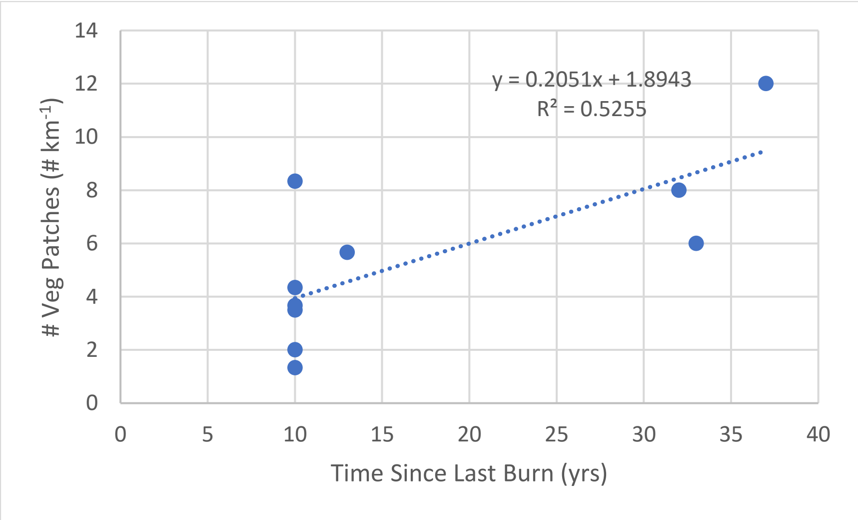


Figure 15. Relationship between the time since last burn (yrs) and number of vegetation patches (# km^{-1}) resulting from 10 spring prescribed fires in the northern Jarrah forest.

Variables scorched leaves (%), scorch height (m), flame height (m) and bark scorch height (m) all showed significant ($p \leq 0.05$) negative relationships with time since last burn (yrs). Scorched leaves (%) and TSLB (yrs) were correlated with $R^2 = 0.524$ (Fig 16a). Scorch height (m) and TSLB (yrs) were more weakly correlated with $R^2 = 0.245$ (Fig 16b), flame height (m) was strongly correlated with TSLB (yrs) ($R^2 = 0.498$) (Fig 16c) while, and bark scorch height (m) had a weaker relationship with TSLB (yrs) ($R^2 = 0.336$) (Fig 16d). The results of these correlations suggest that as the time since the last burn increases we find a decrease in fire intensity. This was an unexpected result since it was assumed that the older stands had a greater fuel load and would burn more intensely. This idea of a greater fuel load is evident in the relationship between canopy cover (%) and TSLB (yrs) which showed a significant ($p \leq 0.05$) positive correlation ($R^2 = 0.334$) with canopy cover increasing with time since last burn (Fig 16e).

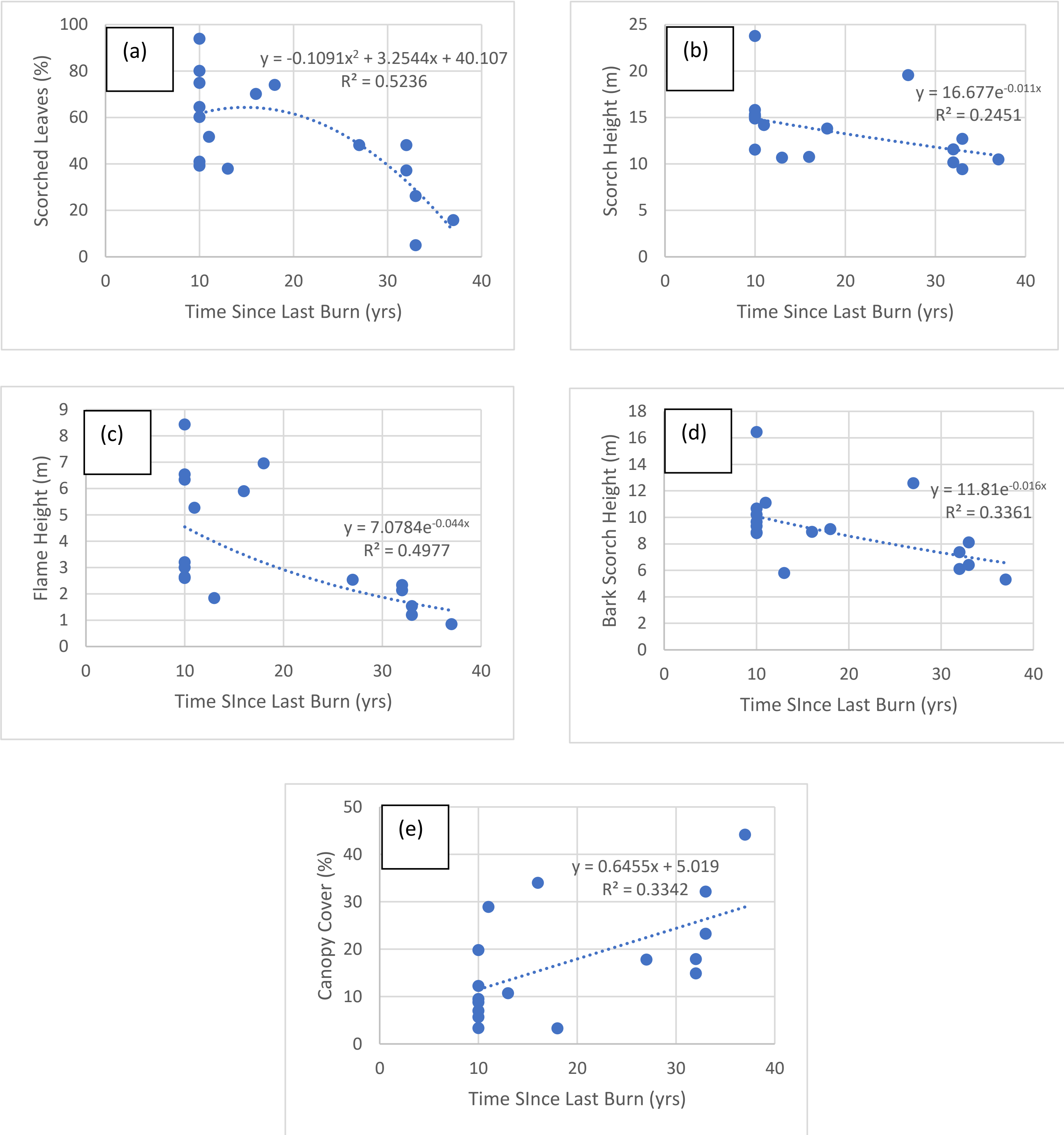


Figure 16. Relationship between time since last burn (yrs) and (a) scorched leaves (%), (b) scorch height (m), (c) flame height (m), (d) bark scorch height (m), and (e) canopy cover (%), for 17 out of 18 prescribed fires surveyed in the northern Jarrah forest. Survey site 8, PHS_006 Woondowing, does not have a recorded time since last burn (yrs).

Surface Moisture Content showed a significant ($p \leq 0.05$) positive correlation with TSLB (yrs) ($R^2 = 0.506$) which suggests that prescribed burn sites with longer intervals between fires were ignited at a time of day where surface moisture content (SMC) was higher (Fig 17).

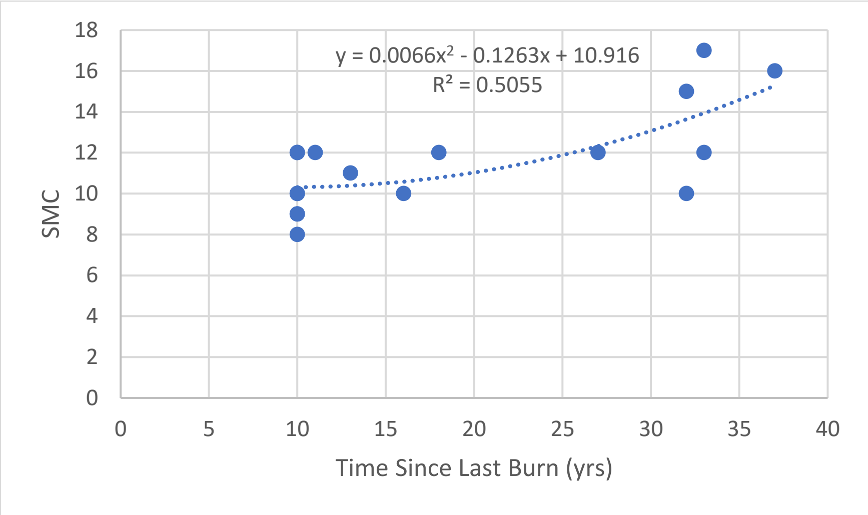


Figure 17. Relationship between the Surface Moisture Content and time since last burn (yrs) determined before the commencement of a prescribed fire in the northern Jarrah forest.

3.7 Model containing the 'best' patchiness creating variables - GLM and Akaike

The AICc values showed that models 1 and 2 are most parsimonious (AICc < 2) with $\Delta_¡$ calculations showing that model 2 is considered equally likely as model 1 ($\Delta_¡ \leq 2$) (Table 4). Wi indicate that model 1 (wi = 0.47) is the most parsimonious out of the 2 candidate models. Model 1 contains the least number of variables (7) and these include: Habitat trees (#), FDI, windspeed (km/h), ash cover (%), area burnt (%), basal char severity (categorical), and month of fire (categorical) (Table 4).

Table 4. GLM analysis results on the 10 environmental variables obtained from the field, the dependent variable is # veg patches. Only models with an AIC <2 are shown. The most parsimonious model (AICc <2) is highlighted. Models were built using a generalised linearnonlinear routine with a Normal Link function. The second order Akaike Information Criterion (AICc), difference in AICc with the top model (Δ¡) and Akaike weight (w¡) are presented for the 4 models. n = 51. Variables: FDI: Fire Danger Index, SMC: Surface Moisture Content, WS: Windspeed (km/h), AC: Ash cover (%), AB: Area burnt (%), BCS: Basal char severity (Categorical), F Hgt: Flame height (m), MF: Month of fire (Categorical), HT: Habitat trees (#), MT: Max temperature (°C).

GLM Models																	
Model No.	Var.1	Var.2	Var.3	Var.4	Var.5	Var.6	Var.7	Var.8	Var.9	Var.10	Degr. of Freedom	AIC	L.Ratio Chi^2	p	AICc	Δi	Wi
1	AB	BCS	MF	FDI	WS	HT	AC				7	249.237	75.321	0.00	251.841	0	0.47
2	AB	BCS	MF	FDI	SMC	WS	HT	AC			8	249.555	77.003	0.00	252.984	1.14	0.26
3	AB	F HGT	BCS	MF	FDI	WS	HT	AC			8	250.701	75.857	0.00	254.129	2.29	0.15
4	AB	BCS	MF	FDI	MT	WS	HT	AC			8	251.100	75.458	0.00	254.529	2.69	0.12

3.8 The final four patchiness creating variables - (SEM)

The SEM showed that the variables within model 1, WS and MF, AC and BCS, AC and HT, and WS and FDI are significantly correlated ($P \leq 0.05$). The three variables that were the least informative out of the six, based on the field surveys, were removed from the final data set. These included WS, BCS and HT. The remaining four experimental variables (FDI, AC, AB and MF) and the dependent variable (VP) were analysed using SEM.

3.8.1 Significant correlations between the dependent and independent variables

The Regression Weights show that there is only one significant correlation ($P \leq 0.05$) between the dependent and independent variables, this being #veg patches and area burnt (%) (Fig 18). The significant correlations indicate that with a reduction in area burnt (%) there is an increase in #veg patches. This indicates that area burnt is the driver variable in predicting patchiness. Area burnt is an influential driver variable having the strongest linear correlation (-0.712).

3.8.2 Significant correlations between the independent variables

The Covariance's show that there are no significant correlations ($P \leq 0.05$) between the independent variables. The Coefficient of Variation (r^2 value) indicates that the independent variables explain 55.5% of the variation in the number of veg patches km^{-1}. The final model consists of the variables FDI, AC, AB, MF and the dependent variable VP (Fig 18).

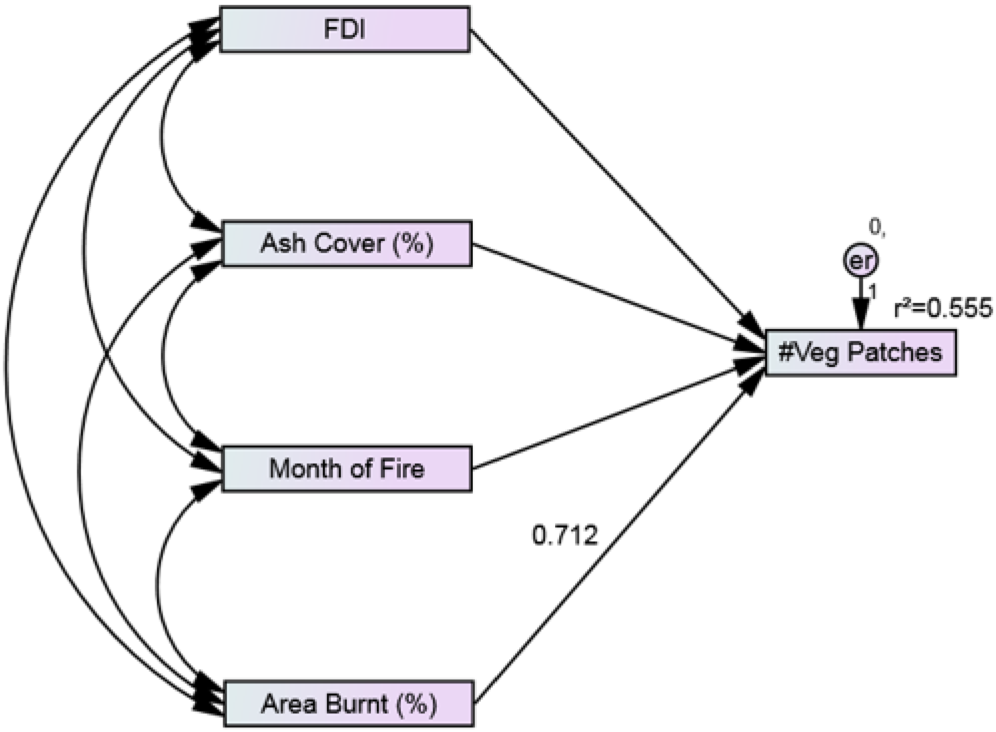


Figure 18. Path Diagram showing the significant linear correlations and standardized regression weights between the 5 variables in model 1. Only significant relationships have weighted coefficients shown.

3.9 Comparison of current DBCA post-burn survey data with the patchiness survey

Five out of 18 prescribed burns were not evaluated or assessed post fire by Parks and Wildlife Service (Table 5). Twelve prescribed burns were assessed with success criteria 1, 11 of which met the criteria (Table 5). All burns assessed with success criteria 2, met the criteria, while only 2 out of 5 burns assessed with success criteria 3, met criteria 3. Six burns were assessed with success criteria 4, with only 1 burn meeting the criteria. All burns assessed with success criteria 5 and 6 were met (Table 5). Basically, these results show that more than 70% of the area was burnt with a mosaic of scorch heights recorded. The burns where criteria were not met were those where the area burnt exceed the desired amount and where there were extensive areas of defoliation.

The post-fire survey data obtained in this study (Table 6) shows that the patchiness of the burns varied (0-12 patches) considerably and this variability is not reflected in the post-fire observations undertaken by the Parks and Wildlife Service (Table 5). This difference was a result of the evaluations not being undertaken (6 out of 18 burns were not assessed with success criteria 1) or the consistency in the observations (11 of 12 burns met success criteria 1). The burns that met success criteria 1 had a highly variable number of patches ranging between 1.3 and 11.3 patches km^{-1}. It is also interesting to note that the single burn that did not meet success criteria 1 (Table 5, Randall 1) had a mid-range number of patches (6).

The accuracy and precision presented by the post-fire survey on the percentage of area burnt (Table 6) is not reflected in the post-fire observations undertaken by Parks and Wildlife Service (Table 5). The percentage of area burnt varied across the 18 sites, ranging from 79.6% to 100% (Table 6). The observations by Parks and Wildlife Service showing that success criteria 2 and 5 were achieved by 12 burns (Table 5) is thus supported by the post-fire survey, which showed that the minimum percentage of burnt area was achieved. Two out of 5 burns met success criteria 3 (Table 5). One of the two burns had 86.6% area burnt and a notably large Standard Deviation of 23.2, and the second burn had an average burnt area of 96.3%, (STdev = 2.0). The three burns which did not meet success criteria 3 had between 83.7% - 97.9% area burnt.

The Parks and Wildlife Service post-fire observations showed that only one of the prescribed burns, out of six, met success criteria 4 (Table 5). The post-fire survey data (Table 6) showed that the burn which met criteria 4 (Table 5, Serpentine NP3) had a mean scorch height of 9.4m and 5% scorched leaves in the canopy (Table 6), supporting the Parks and Wildlife Service's evaluation for the burn. The 5 burns that did not meet success criteria 4 had scorch heights ranging from 11.5m – 15.3m and between 41% - 80.1% scorched leaves in the canopy. It is worth mentioning that the two burn sites with the lowest percentages of scorched leaves recorded had significantly high standard deviations (Table 6, Victoria 2 22/10/2015, and Reservoir).

Table 5. Post-burn assessment/evaluation of success criteria completed by Parks and Wildlife Service for each of the 18 prescribed burn sites. The evaluation is a Yes/No/Partially statement in relation to the success criteria stated in the prescribed fire plan for each site. Not all success criteria are given in each prescribed fire plan. Where a success criteria is not listed as a criteria for a particular site (i.e. does not apply for that site), it is shown with a '–' symbol.

	Parks and Wildlife Service, DBCA, evaluation: success criteria achieved (Y/N)					
	1	2	3	4	5	6
Site	A mosaic of scorch heights and fire intensities is achieved across the burn area	At least 70% of the treatment area is burnt	No more than 90% of treatment area is burnt	No significant areas of continuous defoliation	At least 80% of the treatment area is burnt	There is less than 20% full crown defoliation on steep slopes (Note: full defoliation is common in these terrain types under normal bushfire conditions).
PHS_015 Moondyne	Yes	yes	yes	-	-	-
PHS_066 Reservoir	-	yes	-	No	-	-
PHS_067 Holyoake1 (28/04/2015)				No evaluation		
PHS_043 Amphion_Plavins				No evaluation		
PHS_037 Serpentine NP3	Yes	Yes	-	Yes	-	-
PHS_046 Dale	Yes	Yes	Partially	-	-	-
PHS_006 Woondowing NR	Yes	-	-	-	Yes	-
PHS_060 Victoria 2 (24/10/2015)	Yes	-	-	No	Yes	-
PHS_060 Victoria 2 (22/10/2015)	Yes	-	-	No	Yes	-
PHS_060 Victoria 2 (26/10/2015)	Yes	-	-	No	Yes	-
PHS_046 Dale (South Burn)	Yes	Yes	Partially	-	-	-
PHS_067 Holyoake1 (21/09/2015)				No evaluation		
PHS_056 Randall 1	No	Yes	No	-	-	-
PHS_063 Geddes	Yes	Yes	Yes	-	-	-
PHS_060 Victoria 2 (21/10/2015)	Yes	-	-	No	Yes	-
PHS_020 Zamia	Yes	-	-	-	-	Yes
PHS_071 Nockine_Qualen_Dale				No evaluation		
PHS_034 Serpentine NP 1				No evaluation		

Table 6. Within fire post-burn patchiness of 18 prescribed burn sites in the post-burn surveys undertaken in this study. Selected variables were used in this assessment and these were chosen to be comparable to the variables assessed in the post-burn assessments completed by the Parks and Wildlife Service.

	#Veg Patches		Area Burnt (%)		Scorch Hgt (m)		Scorch leaves (%)	
Site	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
PHS_015 Moondyne	2.7	4.6	86.6	23.2	10.8	2.4	70.2	31.5
PHS_066 Reservoir	4.3	4.0	91.8	9.1	14.2	4.8	51.7	42.5
PHS_067 Holyoake1 (28/04/2015)	0.0	0.0	100.0	0.0	23.8	3.3	74.9	22.9
PHS_043 Amphion_Plavins	0.3	0.6	99.9	0.2	19.6	2.9	48.1	32.5
PHS_037 Serpentine NP3	11.3	4.7	79.6	15.4	9.4	2.2	5.0	4.6
PHS_046 Dale	7.7	7.0	92.0	8.7	11.6	2.9	48.1	37.7
PHS_006 Woondowing NR	6.3	4.2	84.7	18.5	11.9	2.4	53.1	13.6
PHS_060 Victoria 2 (24/10/2015)	3.7	3.1	93.8	5.8	15.3	0.3	80.1	7.6
PHS_060 Victoria 2 (22/10/2015)	8.3	4.5	89.2	8.1	11.5	3.7	41.0	20.2
PHS_060 Victoria 2 (26/10/2015)	1.3	1.5	99.2	0.7	14.9	2.8	60.2	7.9
PHS_046 Dale (South Burn)	8.0	8.5	83.7	14.7	10.2	0.1	37.2	24.6
PHS_067 Holyoake1 (21/09/2015)	2.0	2.6	99.0	1.3	15.8	2.8	39.2	29.0
PHS_056 Randall 1	6.0	5.6	97.9	2.3	12.7	3.0	26.2	13.4
PHS_063 Geddes	5.7	2.5	96.3	2.0	10.7	2.3	38.0	43.8
PHS_060 Victoria 2 (21/10/2015)	3.5	0.7	96.6	0.9	15.2	1.2	64.5	4.0
PHS_020 Zamia	3.0	2.8	92.7	9.0	13.8	2.1	74.0	36.3
PHS_071 Nockine_Qualen_Dale	4.3	5.1	82.5	20.5	15.1	1.0	94.0	7.5
PHS_034 Serpentine NP 1	12.0	7.1	86.2	12.2	10.5	1.1	15.8	3.5

Discussion

The major finding of this study was that within-burn pyrodiversity, seen as the patchiness in forest structure created by variation in burn severity, appears to be low. Results from the prescribed burns in the northern Jarrah forests showed that in most prescribed fires 90 - 100% of the vegetation area was burnt with a limited number of unburned patches (up to 12 km^{-1}) remaining, with most of these unburned patches being small in length (<10 m in length). Although successful for fuel reduction burning, such large-scale vegetation loss could lead to structural homogenisation within a burn area, which in turn could result in long-term impacts on biodiversity.

4.1 Relationships between fire intensity variables and patchiness

It was found that as the fire intensity increased, the number of patches decreased post-burn. Leonard *et al.* (2014) showed that as a fire moves through an area, the higher the intensity of the fire, the less likely that unburnt vegetation patches will remain. The unburnt vegetation patches that occurred within my study varied in length and number km^{-1} over the burn area which is largely due to differences in fire intensity. Turner *et al.* (1997) studied the effects of fire size and pattern on early succession in Yellowstone National Park and found that differential fire intensities play a role in the creation of large and small patches. My results show that an area can have a large number of patches km^{-1}, however most of the patches are small, 1 – 10m in length, while the remaining area was completely burnt.

Fuel moisture also influences the creation of small patches, with Heemstra (2007) showing that two high fire intensity, post-burn survey sites (Blackbutt and Shadow Crossing) were found to have a number of small unburnt patches. The small patches at the 'Blackbutt' site, were a result of an increase in fuel moisture since patches were located along creek lines where there were increased moisture levels. The small patch lengths and large burn area at the second site in Heemstra's (2007) study, 'Shadow Crossing', were attributed to the area having similar slopes and aspect, uniform fuel loading and few barriers. The 18 study sites within my study varied in length, location, topography, aspect and fuel age as well as presence of water bodies and valleys. It is thus suggested that fuel moisture, topography, aspect, fuel loading and barriers, together with high fire intensity, facilitated the creation of small patches within the study's survey sites.

It was found that within a survey site, each of the three templates surveyed presented different patch lengths and numbers, with some templates presenting zero patches. This variability was also seen across the 51 templates surveyed over 18 study sites. These findings support the choice of survey method in terms of capturing the variability across the burn.

4.2 Relationship between pre-fire condition variables and fire intensity

The variables FDI, SMC, windspeed (km h^{-1}) and max temp (°C) are pre-fire condition variables calculated to determine if the weather and environmental conditions on the day of the burn are suitable to: 1) ignite the prescribed burn, 2) meet the designated prescribed burn criteria, and 3) keep the behaviour and intensity of the fire under control. The ability to control fire is a major consideration in all prescribed burning operations carried out in Australian forests (Smith *et al*. 2004) and thus a very tight set of weather conditions are prescribed and as such could have a constraining effect on the creation of patches.

SMC is known to be correlated ($p \leq 0.05$) with fire intensity and any increase in SMC generally results in reduced fire intensities. Heemstra (2007) showed the significant influence moisture had on patchiness in fires in south-east Australia and suggested that fuel moisture largely originates from rainfall, with recent rains particularly increasing fuel moisture content. High fuel moisture constrains and hinders the ignition and carry of the fire and as a result can lead to increased patchiness (Eberhart and Woodard 1987, Hobbs *et al.* 1984). Sneeuwjagt and Peet (1985) suggested that for Jarrah forests a SMC during the day of between 6 and 10 is too dry for prescribed burning, whereas SMC values of 10 and 18 are considered ideal for prescribed burning. SMC values of 18 to 25 leads to poor ignition and very patchy burns while values over 25 are considered too wet for ignition. Over the 18 sites measured in my study the SMC values ranged from 8 to 17, with four burn areas having a SMC that fell below that classed as the ideal prescribed burning SMC range.

Burns are ignited at a specific time of day where the SMC of the area corresponds to the prescription developed for the burn (M Pasotti, 2017 pers com). For example, if a prescribed burn is required to achieve high fire intensity, as stated in the burn fire plan, the ignition spots are ignited closer together and at a time of day with lower SMC. In contrast, a burn lit to achieve a significant number of vegetation patches will be ignited earlier in the day with a higher SMC and ignition spots lit further apart, or alternatively, lit very late in the day, when the SMC is rising so that the area burns out overnight under mild conditions (M Pasotti, 2017 pers com).

In this case, it is possible that these four burns which are at the dry end of the SMC recommendations, were intended to burn hotter and as such, were ignited at a lower SMC. However, burning of very dry vegetation often leads to large and intense fires with significant impacts on with-in burn patchiness and potential long-term effects on biodiversity (Smith *et al*. 2004; Griffiths *et al*. 2015).

In my study, fire intensity was not strongly related to max temp (°C), month of fire, FDI and windspeed (km h^{-1}) which suggests that these four pre-fire condition variables were not significant indicators or predictors of fire intensity and fire behaviour in these prescribed burns. According to Mori and Johnson, (2013), wildfire is extremely sensitive to the climate, and weather variables including temperature and windspeed and these are important determinants of wildfire activity. Month of fire is also an important factor as temperatures increase in summer months, promoting drought and creating more wildfire-prone conditions (Mori and Johnson, 2013). These three variables are thus indicators or predictors of fire intensity within wildfires however are not as important in prescribed burns possibly as a result of the selection of low fire danger days on which prescribed burns are carried out. In other words, prescribed burns are constrained within days that present low fire danger and environmental variables so it is not unexpected that these variables are not important in controlling fire intensity.

Max temperature, windspeed, FDI and month of fire are all considered prior to the ignition of a prescribed burn (M Pasotti, 2017 pers com). Month of fire for prescribed burning is relatively consistent which may explain why month of fire does not correlate with fire intensity. Max temperature is not considered a big driver of fire behaviour in prescribed burning (M Pasotti, 2017 pers com). Temperature is simply an input into the FDI and Parks and Wildlife Service burn to the FDI. As a result, temperatures can fluctuate and the FDI can stay the same as other variables override the impact of temperature which is why we have seen little correlation between fire intensity and temperature (M Pasotti, 2017 pers com). Windspeed is also an input into FDI and is one of the main drivers of FDI which makes this result found in this study surprising, however, it is purely an input and has the same effect as temperature in that it can be overridden by other weather variables (M Pasotti, 2017 pers com). This may explain why I did not see a strong correlation between windspeed and fire intensity.

4.3 Relationship between post-fire fire intensity variables, pre-fire condition variables and patchiness

Scorched leaves (%) and flame height (m) were significantly ($p \leq 0.05$) related to fire intensity as well as negatively correlated with the number of patches. Additionally, it was found that variables scorched leaves (%) and flame height (m) significantly correlated with the pre-fire condition variable SMC. This suggests that scorched leaves (%) and flame height (m) are both suitable indicators of fire intensity and fire behaviour as well as being significantly related to patchiness. In other words, fire intensity is negatively related to patchiness (an increase in fire intensity will decrease patchiness). Turner *et al*. (1997) found that variation in fire intensity influenced the size of patches remaining post fire. My study has shown that by calculating SMC prior to the burn, fire intensity variables scorched leaves (%) and flame height (m) can be predicted and influenced, allowing organisations/companies the ability to manage and predict fire intensity and patchiness of a prescribed burn. The findings from this study indicate that fire intensity and SMC correlate with patchiness and can therefore be used to predict patchiness.

The variable canopy cover, defined as the percentage of remaining unburnt tree canopy, was found to not be related to patchiness, however it had a significant positive relationship with the pre-fire condition variable SMC. Canopy cover can create a degree of spatial variation amongst surface temperatures as a result of spatial variations in root-zone soil water, different soil drying rates and vegetation physiology (Nemani 1993). This suggests that although SMC and canopy cover are correlated, and SMC can be used to predict the percentage of remaining and burnt canopy cover, canopy cover does not influence patchiness at the ground level. Therefore, only intensity variables scorched leaves (%) and flame height (m) are influenced by pre-fire conditions and both can be used to indicate patchiness.

4.4 Patch number and length over spring and autumn

Prescribed burns in spring and autumn were not found to be significantly different in terms of the mean patch length and total number of vegetation patches post-burn. Although the season of burn was not important, patch lengths were found to vary across a burn area. The study showed that both autumn and spring burns had patches varying in length and a large percentage of patches identified within post prescribed burn survey sites were between 1 -10 m in length, followed by patches 11-20 m in length. As indicated previously, a high number of small patches within a site, and no large patches, indicates a high fire intensity and variations in fuel moisture levels. Variability across the burns has been captured, with burn sites presenting patch lengths across the range with the largest patch being between 201-300 m in length and the smallest 1 - 10 m in length with both within the same burn site (PHS_015 Moondyne). This variability in patch lengths can be attributed to the means by which patches are created (Heemstra, 2007).

Heemstra, (2007) showed that there are two different types of unburnt patches that can be created post-burn. The first type of patch includes areas that did not burn because they could not burn as a result of reduced fuel ignition. Patches under type 1 can be caused by low fuel loads, vegetation types with a low probability of combustion, different vegetation community types, high fuel moisture (creeks, lakes, rainfall, shading, sheltering), proximity to permanent water bodies (rivers, wetlands, dams), topography (elevation, slope and aspect effect fuel moisture), temperature and humidity, and weather (wind, rainfall). The second type of unburnt patch are areas that could have, but did not burn, due to the effect of barriers restricting a fire's passage. These barriers include areas of zero fuel (fire trails, walking tracks, animal tracks, cliffs, rock ledges and ridgelines), water bodies, low wind and ignition method. Cleared areas from animal nest building, logs and large tree trunks can also result in small unburnt patches at a fine scale. A combination of both type 1 and type 2 effects are generally seen to create patchiness (Heemstra 2007). The post-burn vegetation patches within my study are influenced by fire intensity and SMC, both of which are seen to create type 1 patches. Some patches within this study are potentially a combination of type 1 and 2 effects since burn sites generally had walking and/or car tracks within the burn area acting as potential barriers hindering the fire's route.

4.5 Time since last fire relate to vegetation patches

Within the northern Jarrah forest, it was found that the longer the period of time between prescribed burns in an area, the greater the number of vegetation patches km^{-1} that occurred post fire. Fuel loads increase with time since fire (Burrows et al, 2010) and according to previous studies (Slocum, 2003, Heemstra, 2007, and Burrows et al, 2010), high fuel loads and extreme conditions may result in a high intensity fire and low patchiness. Areas that have experienced recent fire have lower fuel loads and as a result, patchiness is enhanced (Slocum, 2003; Heemstra, 2007). The results within my study contrast with this literature, with post-burn study sites showing that an increase in time since last burn (TSLB) leads to an increase in the number of vegetation patches km^{-1} within a burn perimeter.

This study found that fire intensity decreased with an increase in time since last burn (TSLB). A decrease in fire intensity has been shown to lead to an increase in patches, therefore it is possible that the negative correlation between fire intensity and TSLB explains the increase in number of patches km^{-1} with TSLB. The decrease in fire intensity within the study sites can be explained by the significant correlation ($p \leq 0.05$) between Surface Moisture Content and TSLB, showing that SMC increases with an increase in TSLB. Earlier studies by Sneeuwjagt and Peet, (1985), and Burrows, (1994) showed that an accumulation of available fuel levels, with low fuel moisture levels, can result in an increase in fire intensity, alternatively, an increase in fuel moisture levels can increase the number of patches post-burn (Knapp and Keeley, 2006) and reduce fire intensity (Heemstra, 2007).

The increase in SMC with TSLB within the study sites may be attributed to thicker and denser fuel beds as they are known to dry out more slowly and considerable fuel moisture will persist where there is high fuel accumulation, especially in spring and autumn times of prescribed burning (Sneeuwjagt and Peet, 1985; Burrows, 1994.). In addition, it is known that SMC and weather variables vary over the day, and as such, prescribed burns are ignited at a specific time of day, determined by the weather and pre-fire conditions to best control the burn and achieve to prescribed burn outcome (M Pasotti, 2017 pers com). This may also explain the high SMC values with TSLB as prescribed burns that are to be carried out in an area that has a large time since last burn value, Parks and Wildlife Service will ignite these fires generally at higher SMC so as to counter act the high fire intensities that are associated with areas presenting large fuel loads (M Pasotti, 2017 pers com). It has been found that SMC reduces fire intensity thus, the increase in surface moisture content can explain the decrease in fire intensity and the increase in patches with TSLB.

SMC has been found to reduce fire intensity, however another method of reducing fire intensity is to increase burn frequency (M Pasotti, 2017 pers com). Fuel loads increase with TSLB, and a rise in fuel loads is known to increase fire intensity (Burrows et al, 2010). Thus, an increase in burn frequency will reduce the fuel load quantity and can result in the increase of within-burn mosaic and heterogeneity of jarrah forest prescribed burns (M Pasotti, 2017 pers com). Parks and Wildlife Service currently burn on a 10 - 15 year frequency. Within jarrah forests, fuels 7 years and older are more likely to burn at a higher intensity and have low internal mosaics. Within older fuels, burning under a low FDI in order to manage fire behaviour is not ecologically suitable and has significant security risks (M Pasotti, 2017 pers com). Therefore, the higher the frequency, the milder the burn and the more heterogenous result.

4.6 Variables that strongly indicate patchiness

Generalised Linear Modelling and AICc showed that the four variables FDI, ash cover (%), area burnt (%) and month of fire were the 'best' at explaining patchiness. The SEM and path diagram (Fig 18) showed that the most influential, 'driver', variable in predicting patchiness was area burnt (%). None of the final explanatory variables were significantly correlated with each other and all contribute to patchiness at different levels. The four most parsimonious variables all predict different types of patches created via different effects including the effect of barriers and/or the ability of fuel to be ignited (Heemstra, 2007). The FDI is a pre-fire condition variable and can indicate several type 1 patches, including patches created by high fuel moisture, temperature, humidity and weather conditions including wind and rainfall (Heemstra, 2007). The percentage of ash cover is a fire intensity variable and determining the percentage of ash cover within a burn can indicate patches created by low fuel loads, different vegetation community loads, areas of zero fuel and topography including slope, elevation and aspect (Heemstra, 2007). The variable month of fire indicates fuel characteristics and weather and as such can indicate several type 1 patches, including patches created by low fuel loads, high fuel moisture, proximity to water bodies, weather, temperature and humidity (Heemstra, 2007). The percentage of area burnt determines the overall patchiness as well as the length and number of patches, remaining post-burn. Although this shows that some of the final four most parsimonious variables collect data on the same patch types, it is evident that the four variables when assessed together, cover the range of vegetation patch types presented post burn.

The SEM and path diagram shows that out of the four 'best' patchiness explaining variables (FDI, ash cover (%), area burnt (%) and month of fire) the variable area burnt (%) is the only significant predictor of patchiness, the remaining three variables are not significant predictors. Thus, the variable area burnt (%) is the 'best' patchiness explaining variable. This indicates that by quantitatively surveying the single variable area burnt (%), the patchiness of a within-burn area post fire will be determined and intern indicate pyrodiversity and potential homogenisation of the area. The quantitative measurements obtained will allow records to be stored and for future analysis of the results.

4.7 Comparison between DBCA post-fire surveys and this study

The current Parks and Wildlife Service post-burn survey and the survey designed for this thesis to determine the patchiness of the within burn area post-burn was compared to see how similar the results were between the two evaluations. The Parks and Wildlife Service post-burn assessment completed for the 18 burn sites showed that data collected for the survey was a yes/no/partially answered assessment against the success criteria stated in the prescribed fire plan. The data and information was obtained from estimates of area burnt and fire intensity and was later added to the documented prescribed fire plan as part of the post-burn assessment section (M Pasotti, 2014 pers com). Although the post burn assessments were completed, the survey method and information collected on the variables was not sufficient to describe the variability over the burn site and thus indicate patchiness. Comparing the two post burn surveys showed that there were large differences in the results.

The post-fire survey in my study used visual estimates together with measurements on 29 environmental variables with quantitative data recorded. The data collected from the burn sites were then further analysed to determine patchiness. It has been found that patchiness can be quantified through measuring the variable area burnt (%). The post-fire survey results in my study showed that the patchiness of the burns varied considerably and the quantitative data obtained provided good insights into fire patchiness, fire intensity and variability and thus it might be valuable for future studies investigating the effect of fire characteristics on biodiversity in these managed forests. The post-fire survey data also provided a reliable, in-depth evaluation of the burn patterns and specifically the patchiness within burns.

It is clear from the comparison that quantitative measurements of post-burn characteristics are required to give a thorough and more rigorous understanding of what the prescribed burn has achieved. This supports the idea that a post-fire patchiness survey similar to that designed for my study should be developed as a future management option especially in cases where enhanced biodiversity outcomes is included as a part of the prescribed burning plan.

4.8 Prescribed burning and possible within-burn homogenisation

The percentage of area burnt across all sites was high, with the majority of the templates having between 90% – 100% vegetation burnt. Patch lengths were mostly small being mainly restricted to 1 – 10 m in length. According to Kolasa and Rollo (1991) an environment may be deemed to be spatially heterogeneous ‘if the rate of a process varies over space in relation to structural variations of the environment’. According to the Disturbance Heterogeneity Model (DHM, Kolasa and Rollo 1991) heterogeneity in communities is highest when around 50% of an area is disturbed (Kolasa & Rollo, 1991) while the Intermediate Disturbance Hypothesis (IDH, Connell, 1978) suggests that heterogeneity within-patch will be highest at intermediate frequencies of disturbance (Collins, 1992). These ideas suggest that very regular burning of more than 50% of any landscape or area will lead to homogenisation in structure and function of that vegetation type. The environment may be considered homogenous if a process has a uniform rate across space (Kolasa & Rollo, 1991). It was found in my study that 94% of post prescribed burn areas within the Perth hills Jarrah forest have 80 – 100% of area burnt with few small patches remaining which raises concerns that the within fire pyrodiversity is low and as a consequence homogenization of the within-burn area is a potential concern.

It is worth noting that although homogenisation may occur within prescribed burn areas, this is not necessarily a negative outcome in terms of landscape patchiness. On a landscape scale, burns that have a high internal % burnt are still just a patch within their landscape and usually represent less than 1% of that landscape (M Pasotti, 2017 pers com). The objective of fuel management is to reduce the likelihood of a fire event that will cover very large areas at high intensity (5+% of the whole landscape) by burning multiple smaller patches. While internal patchiness is normally aimed to be between 10-30% unburnt, it isn't necessarily a negative outcome from a landscape scale if there is a higher % burnt achieved (M Pasotti, 2017 pers com).

4.9 Significance of determining within burn patchiness

Prescribed burning results in the generation of a mosaic of successional stages across a landscape (Abbott *et al*. 2003), and can result in a mosaic of scorch heights and fire intensities within a burn perimeter (M Pasotti, 2014 pers com). Mosaic is defined as the spatial arrangement of unburnt and burnt fuels at a landscape or a local scale (DBCA, 2017). There have been many studies on fire effects on landscape mosaics (Faivre *et al*. 2011; Maravalhas and Vasconcelos, 2014; Kelly *et al*. 2014; Griffiths *et al*. 2015; Ponisio *et al*. 2016), however local and within-burn mosaic studies are more limited and little research has been undertaken on the effects of within-burn patchiness on biodiversity. Of the studies that have focussed on the relationship between pyrodiversity-biodiversity most have focussed more on the relationship biodiversity has with fire frequency and/or fire intensity rather than the relationship with patchiness (Maravalhas and Vasconcelos, 2014; Griffiths *et al*. 2015; Ponisio *et al*. 2016). A study completed by Tingley *et al*. (2016), looked at within-burn patchiness and bird diversity, investigating how bird communities were affected by heterogeneity in severity within wildfires in the montane forests of inland California. They found that individual fires with a greater variety of burn severities had significantly more bird species than areas experiencing fires with more homogenous fire intensities. The demonstration that patchiness (caused by varying fire intensity) within a burn influences the diversity of bird species (Tingley *et al*. 2016) suggests that more research is needed across a range of ecosystems to determine the effects on other fauna and flora. To do this will require informative data on fire properties recorded from post burn assessments that can be used to evaluate the impact of the fires on biodiversity at different times after the fire.

The majority of prescribed fires assessed in this study had a success criteria stating that a mosaic of scorch heights and fire intensities was to be achieved across the burn area. This within burn mosaic or patchiness was assessed by both the Parks and Wildlife Services post burn assessment and the survey designed for my study with results showing that quantitative measurements, as presented in this thesis, are required to effectively, and accurately, determine this criterion. It was found that by assessing patchiness, by calculating the variable area burnt (%), the percentage of burnt and unburnt area within the burn can be determined as well as fire intensity and behaviour.

Synthesis and Conclusion

The three objectives of this study have all been achieved. It was found that prescribed burning in the northern Jarrah forest has the potential to homogenise landscapes within the burn area. A large number of the prescribed burns surveyed showed high fire intensities with few, small patches of remaining vegetation. Although the season of burn showed no significant differences between the mean patch length and total number of vegetation patches, the length of the vegetation patches were found to vary within a post-burn area. Vegetation patches were found to be significantly influenced by both fire intensity and surface moisture content. This was further supported by findings indicating that both SMC and fire intensity facilitated the creation of, and increase in, the number of vegetation patches with time since last burn. It can thus be concluded that SMC and fire intensity are significant contributors to the creation of patches under prescribed burning conditions.

Generalised Linear Modelling and AICc showed that four fire intensity and patchiness indicating variables (Fire Danger Index, ash cover (%), area burnt (%) and month of fire) are most important for the creation of patchiness. Further analysis through Structured Equation Modelling has shown that the variable area burnt (%) is the only significant predictor of patchiness. The variable area burnt (%) is considered the most parsimonious and 'best' fit at predicting the patchiness of a prescribed burn area. By determining the patchiness, we can determine if the area is homogenised and using quantitative measurements, to what extent.

Prescribed fire plans for biodiversity/fuel reduction burns generally aim for a mosaic of scorch heights and fire intensities across a burn, with between 70 - 90% burnt area. This was reflected in my results, showing the variability across each burn site in relation to patch length and number, as well as fire intensity. Although some sites were found to have met these criteria, others did not. The percentage of area burnt across the sites was high, with majority of the templates having between 90 – 100% vegetation burnt. Through completion of post burn surveys and literature review, it was determined that prescribed burn post-burn sites with a burn area of between 80 - 100% can be considered to be homogenous. It is thus concluded that majority of the prescribed burn areas surveyed were homogenised and that prescribed burning leads to within-burn area homogenisation.

5.1 Study's Limitations

5.1.1 Data collection

In order to minimise the impact of environmental variables on the data collected in the field, such as rain and wind, surveys should be undertaken as soon as possible after the burn has been declared extinguished and field conditions are considered to be safe. Hazards such as falling branches and trees post fire make getting to site and surveying the area immediately after the burn difficult since access roads into and around the burn site are often closed off due to fallen trees. The post-burn survey used in my study was comprised of three templates which were surveyed at three locations within the burn area. This required access to most, if not all roads surrounding the treated area. The clearing of the roads can take up to several months, depending on the availability of equipment and personnel. The surveys within this study were not completed until several weeks after the day of the burn (between 34 – 138 days post burn). The influence of environmental variables was thus considered in this study and as a result, variables black, grey and white ash cover were considered unreliable and excluded from analysis.

5.1.2 Replication across burn sites

Heemstra, (2007), found that between 10 and 20 transects are required to estimate the percentage of area burnt over a landscape with a sample error of less than 10%. However, the number of transects can be reduced if landscape heterogeneity is maximised by taking into consideration where transects will be placed in terms covering a range of environmental variables such as vegetation type, slope and aspect. The number of transects used in this study's surveys to indicate the patchiness within burn was reduced as the range of environmental variables was taken into consideration and background information on topography, veg type, burn perimeter and basic fire behaviour and intensity was obtained from Parks and Wildlife Service for each burn prior to commencement of a survey. Transects were thus carried out in selected areas to obtain the maximum variation over the burn area. The total length of transects for this study is 3,000 m over 6 transects which is completed for burns ranging from 93 ha in size to 9,855 ha. Heemstra, (2007) determined the patchiness within 12 post burn sites, using a transect sampling pattern derived from topographic maps for each site. One of the smallest burn areas surveyed was 30 ha, with 1 transect that was 1,294m long. The largest burn site surveyed was 1260 ha with 9 transects with a total transect length of 26,278 m. The survey sites within this study are thus considerably larger than the sites surveyed by Heemstra, (2007), although less area was surveyed.

Time was limited and completing more than 6 transects as well as covering more than 3,000 m across the burn area can potentially be quite time consuming. This research also looked at the collection of variables which could not be collected via transect, but instead were collected via quadrats. A survey method was thus designed to capture the variability across a burn by using both transect and quadrat sampling methods. This survey design is considered to be equivalent to the use of just transects for measuring patchiness within a burn. The survey method and design reflect the data collected, to maximise the collection of environmental variables over the burn and capture the variability.

5.1.3 Burn Criteria Compliance

Prescribed burn survey sites were to meet 3 criteria in order to be eligible to be used in the study. The three criteria included:

1. They needed to be treated with a prescribed burn in the 2015 year,
2. The burn area needed to be >2000 ha, and
3. The vegetation of the prescribed burn areas was restricted to predominantly Jarrah forest (forest dominated by *E. marginata*).

Not all prescribed burn sites surveyed in this study met all three criteria. Criteria 1 and 3 were met by all survey sites, however, 10 out of the 18 post burn survey sites did not meet criteria 2, having areas <2000 ha in size. This is a result of low numbers of prescribed burns ignited in the year 2015 and in order to obtain a reasonable sample size, some prescribed burn sites were <2000 ha in size. Post burn areas less than 2000 ha in size had the potential to be too small for the 3 survey templates to fit the within burn area. This meant that at small burn sites the templates were surveyed closer together than desired in order to fit all three templates into the burn area. Results of the patchiness of the small burns did not seem to be substantially different from the larger burns so this limitation is of minor concern.

5.1.4 Comparison of Prescribed fires with Wildfires

Wildfires can homogenise a landscape since they burn at higher intensities, and can be more extensive than prescribed burns (Leonard *et al*, 2014; Alba *et al*. 2015; Griffiths *et al*. 2015). For practical reasons (availability and timing of wildfires could not be planned) this study did not assess homogenisation by wildfires. This meant that I was unable to compare the differences in patchiness within a prescribed burn versus that generated by a wildfire. As a consequence, I am unable to say whether the homogenization effect of prescribed burns is more or less significant than what results from wildfire. Further research is required to explore this idea using the post burn patchiness survey, designed in my study, to assess the within burn area patchiness of wildfires and then compare the results with prescribed burns to determine the relative impact the different burn types have on pyrodiversity.

5.2 Future management recommendations

5.2.1 Reducing the fuel load reduction percentage

It is recognised that success criteria for fuel reduction/biodiversity burns generally requires a minimum of 70% - 80% area burnt, with the minimum value varying between the requirements of individual prescribed fire plans. Prescribed burns that do not meet the minimum percentage of area burnt would not satisfy the fire plans success criteria and possibly not sufficiently reduce fire hazard. It is suggested that a compromise could be considered where fuel reduction of between 70 - 80% of an area (with a maximum of 85%) should be aimed for in a fuel reduction/biodiversity burn in order to sufficiently reduce fuel loads while at the same time creating a more heterogenous post burn area which could have significant biodiversity outcomes.

5.2.2 Post-burn survey implementation

The comparison of the two post-burn assessments, Parks and Wildlife Service and the patchiness survey designed for this thesis, showed that the new post-burn patchiness survey is able to determine the patchiness of a within burn area by quantitatively assessing the variable area burnt (%) that has been statistically determined as the 'best' variable for predicting patchiness. The quantitative measurements recorded are an in-depth look into what the prescribed burn has achieved in terms of patchiness. The patchiness survey is suitable for an alternative post-burn assessment survey in future management actions within Jarrah forest, presenting quantitative measurements that will also be able to be stored and referred to in the future.

The variable area burnt (%) is required to be assessed to determine pyrodiversity and the patchiness of the within burn area. The survey takes on average 5.8 hours to complete. The final survey to be used as a post-burn assessment should consist of the 500m transects. By taking out the quadrats, the time to complete the survey will be reduced. The survey templates remain the same, minus the three quadrats. The length and shape of the template is required to be the same in order to capture the variability across the burn (See figure 19 in Appendix 1 for an updated field survey data sheet). It is also important to recognise that this post-burn survey should only be used for Jarrah forest since other forest types have different vegetation types, fuel loads and fire behaviour all of which can affect the generation of with-in burn patchiness.

References

Abbott, I., Burbidge, T., Strehlow, K., Mellican, A., & Wills, A. (2003). Logging and burning impacts on cockroaches, crickets and grasshoppers, and spiders in Jarrah forest, Western Australia. *Forest Ecology and Management*, 174: 383-399.

Alba, C., Skalova, H., McGregor, K. F., D'Antonio, C, & Pysek, P. (2015). Native and exotic plant species respond differently to wildfire and prescribed fire as revealed by meta-analysis. *Journal of Vegetation Science,* 26: 102-113.

Alexander, M. E., & Cruz, M. G. (2012). Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. *International Journal of Wildland Fire,* 21: 95.

Andersen, A. N., Ribbons, R. R., Pettit, M., & Parr, C. L. (2014). Burning for biodiversity: highly resilient ant communities respond only to strongly contrasting fire regimes in Australia's seasonal tropics. *Journal of Applied Ecology*, 51: 1406-1413

Anderson, D. R., Link, W. A., Johnson, D. H., & Burnham, K. (2001). Suggestions for presenting the results of data analyses. *Journal of Wildlife Management*, 65: 373-378.

Anderson, P., Brundrett, M., Grierson, P., & Robinson, R. (2010). Impact of severe forest dieback caused by Phytophthora cinnamomi on macrofungal diversity in the northern Jarrah forest of Western Australia. *Forest Ecology and Management*, 259: 1033-1040.

Atahan, P., Dodson, J. R., & Itzstein-Davey, F. (2004). A fine-resolution Pliocene pollen and charcoal record from Yallalie, south-western Australia. *Journal of Biogeography,* 31: 199-205.

Bailey, T. G., Davidson, N.J., & Close, D. C. (2012). Understanding the regeneration niche: Microsite attributes and recruitment of eucalypts in dry forests. *Forest Ecology and Management*, 269: 229-238.

Bain, K., Wayne, A., & Bencini, R. (2016). Prescribed burning as a conservation tool for management of habitat for threatened species: the quokka, *Setonix brachyurus*, in the southern forests of Western Australia. *International Journal of Wildland Fire*, 25: 608-617

Bauerle, H., & Nothdurft, A. (2011). Spatial modeling of habitat trees based on line transect sampling and point pattern reconstruction. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* 41: 715-727.

Bell, D. T., & Heddle, E. M. (1989). Floristic, morphologic and vegetational diversity. In *The Jarrah Forest*, pp. 53-66. Springer Netherlands.

Bell, T. D., McCaw, L. W., & Burrows, N. D. (1989). Influence of fire on Jarrah forest vegetation. In: Dell, B., Havel, J. J., & Malajczuk, N. (eds) The Jarrah Forest: A Complex Mediterranean Ecosystem. Kluwer Academic, Dordrecht, pp. 203-215.

Bisigato, A. J., Villagra, P. E., Ares, J. O., & Rossi, B. E. (2009). Vegetation heterogeneity in Monte Desert ecosystems: A multi-scale approach linking patters and processes. *Journal of Arid Environments*, 73: 182-191.

Bond, W. J., & van Wilgen, B. W. (1996). Fire and Plants. Chapman & Hall, London.

Bond, W. J., Woodward, F. I., & Midgley, G. F. (2005). The global distribution of ecosystems in a world without fire. *New Phytol*, 165: 525-537.

Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson J, M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, C., Roos, C. I., Scott, A. C., Swetnam, T. W., van der Werf, G. T., & Pyne, S. J. (2009). Fire in the Earth System. *Science*, 324: 481-484.

Bradstock, R. A. (2010). A biogeographic model of fire regimes in Australia: current and future implications. *Global Ecology and Biogeography*, 19: 145-158.

Bradstock, R. A., Boer, M. M., Cary, G. J., Price, O. F., Williams, R. J., Barrett, D., Cook, G., Gill, A. M., Hutley, L. B. W., Keith, H., Maier, S. W., Meyer, M., Roxburgh, S. H., & Russell-Smith, J. (2012a). Modelling the potential for prescribed burning to mitigate carbon emissions from wildfires in fire-prone forests of Australia. *International Journal of Wildland Fire*, 21: 629-639.

Bradstock, R. A., Williams, R. J., & Gill, A. M. (Eds.). (2012b). *Flammable Australia: fire regimes, biodiversity and ecosystems in a changing world*. CSIRO publishing.

Brando, P. M., Balch, J. K., Nepstad, D. C., Morton, D. C., Putz, F. E., Coe, M. T., Silvério, D., Macedo, M. N., Davidson, E. A., Nóbrega, C. C., Alencar. A., & Soares-Filho, B. S. (2014). Abrupt increases in Amazonian tree mortality due to drought-fire interactions. 111: 6347-6352, PNAS Publishing.

Burnham, K. P., & Anderson, D. R. (2001). Kullback-Leibler information as a basis for strong inference in ecological studies. *Wildlife Research*, 28: 111-119.

Burnham, K. P., & Anderson, D. R. (2003). Model selection and multimodal inference: a practical information-theoretic approach. Springer Science & Business Media, New York.

Burnham, K. P., & Anderson, D. R. (2004). Multimodel inference understanding AIC and BIC in model selection. *Sociological methods & research*, 33: 261-304.

Burrows, N. D. (2001). Flame residence times and rates of weight loss of eucalypt forest fuel particles. *International Journal of Wildland Fire*, 10: 137-143.

Burrows, N. D. (2008). Linking fire ecology and fire management in south-west Australian forest landscapes. *Forest Ecology and Management,* 255: 2394-2406.

Burrows, N. D., & Wardell-Johnson, G. (2003). Fire and plant interactions in forested ecosystems of south-west Western Australia. In: Abbott, I., & Burrows, N. (eds) Fire in Ecosystems of South-West Western Australia: Impacts and Management. Backhuys, Leiden, pp. 225-269.

Burrows, N., Ward, B., & Robinson, A. (2010). Fire Regimes and Tree Growth in Low Rainfall Jarrah Forest of South-west Australia. *Environmental Management,* 45: 12.

Burrows, N.D., 1994. Experimental development of a fire management model for Jarrah (Eucalyptus marginata Donn ex Sm.) forest. Ph.D. Thesis. Australian National University, Canberra.

Cargill, J. (2014). Fate of Eucalyptus marginata seed from canopy-store to emergence in the northern Jarrah forests of Western Australia: research to help improve regeneration following shelterwood treatment. *Centre for Ecosystem Management, School of Natural Sciences, Faculty of Health, Engineering and Science,* Edith Cowan University. Honours

Cargill, J., Van Etten, E. J., Whitford, K. R., McCaw, L. W., & Stock, W. D. (2016). A refined method for estimating capsule crops in individual Jarrah (Eucalyptus marginata) crowns. *Australian Forestry, 79*: 208-216.

Catling, P. C., & Burt, R. J. (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: 18.

Chambers, D. P., & Attiwill, P. M. (1994). The ash-bed effect in Eucalyptus regnans forest: chemical, physical and microbiological changes in soil after heating or partial sterilization. *Australian Journal of Botany*, 42: 739-749.

Cheney, N. P., Gould, J. S., McCaw, W. L., & Anderson, W. R. (2012). Predicting fire behaviour in dry eucalypt forest in southern Australia. *Forest Ecology and Management*, 280: 120-131.

Davies, A. B., Eggleton, P., Van Rensburg, B. J., & Parr, C. L. (2012). The pyrodiversity-biodiversity hypothesis: a test with savanna termite assemblages. *Journal of Applied Ecology*, 49: 422-430.

Dell, B., & Havel, J. J. (1989). The Jarrah forest, an introduction. In: Dell, B., Havel, J. J., & Malajczuk, N. (eds) The Jarrah Forest: A Complex Mediterranean Ecosystem. Kluwer Academic, Dordrecht, pp. 1-10.

DBCA. (2017). Fire Glossary. Retrieved from https://www.dpaw.wa.gov.au/management/fire

Dixon, K.W., Roche, S., & Pate, J. S. (1995). The promotive effect of smoke derived from burnt native vegetation on seed germination of Western Australian plants. *Oecologia*, 101: 85-192

DPaW. (2013). Planning for prescribed burning. Retrieved from http://www.dpaw.wa.gov.au/management/fire/prescribed-burning/54-planning-for-prescribedburning?showall=&limitstart=.

Faivre, N., Roche, P., Boer, M. M., McCaw, L., & Grierson, P. F. (2011). Characterization of landscape pyrodiversity in Mediterranean environments: contrasts and similarities between south-western Australia and south-eastern France. *Landscape Ecology*, 26: 557-571.

Eberhart, K. E. & Woodard, P. M. (1987). Distribution of residual vegetation associated with large fires in Alberta. *Canadian Journal of Forest Research*, 17: 1207-1215.

Fleming, P. A., Anderson, H., Prendergast, A. S., Bretz, M. R., Valentine, L. E., Hardy, G. E. StJ. (2014). Is the loss of Australian digging mammals contributing to a deterioration in ecosystem function? *Mammal Review*, 44: 94-108.

Franklin, S. B., Robertson, P. A., & Fralish, J. S. (1997). Small-scale fire temperature patterns in upland Quercus communities. *Journal of Applied Ecology*, 34: 613-630.

French, M. (2012). *Eucalypts of Western Australia's Wheatbelt*. Padbury, Western Australia.

Gervais, D. J., Greene, D. F., & Work, T. T. (2012). Causes of variation in wood-boring beetle damage in fire-killed black spruce (Picea mariana) forests in the central boreal forest of Quebec. *Ecoscience*, 19: 398-403.

Gill, A. M., Groves, R. H., & Noble, I. R. (eds) (1981) Fire and the Australian Biota. Australian Academy of Science, Canberra.

Glen, M., Bougher, N. L., Colquhoun, I. J., Vlahos, S., Loneragan, W. A., O'Brien, P. A., & Hardy, G. E. St J. (2008). Ectomycorrhizal fungal communities of rehabilitated bauxite mines and adjacent, natural Jarrah forest in Western Australia. *Forest Ecology and Management,* 255: 214-225.

Gosper, C. R., Yates, C. J., Prober, S. M., & Wiehl, G. (2014). Application and validation of visual fuel hazard assessments in dry Mediterranean-climate woodlands. *International Journal of Wildland Fire,* 23: 385.

Gould, J. S., McCaw, W. L., Cheney, N. P., Ellis, P. F., Knight, I. K., & Sullivan, A. L. (Eds.). (2008). *Project Vesta: fire in dry eucalypt forest: fuel structure, fuel dynamics and fire behaviour*. CSIRO PUBLISHING.

Gould, S. J., McCaw, L. W., & Cheney, P. N. (2011). Quantifying fine fuel dynamics and structure in dry eucalypt forest (Eucalyptus marginata) in Western Australia for fire management. *Forest Ecology and Management*, 262: 531-546.

Griffiths, A. D., Garnett, S. T., & Brook, B. W. (2015). Fire frequency matters more than fire size: Testing the pyrodiversity-biodiversity paradigm for at-risk small mammals in an Australian tropical savanna. *Biological Conservation*, 186: 337-346.

Grigg, A. H., Norman, M. A., & Grant, C. D. (2010). Prescribed burning of thinning slash in regrowth stands of Jarrah (Eucalyptus marginata) following bauxite mining in south-west Australia. *International Journal of Wildland Fire,* 19: 737.

Haslem, A., Avitabile, S. C., Taylor, R. S., Kelly, L. T., Watson, S. J., Nimmo, D. G., Kenny, S. A., Callister, K. E., Spence-Bailey, L. M., Bennett, A. F., & Clarke, M. F. (2012). Time-since-fire and inter-fire interval influence hollow availability for fauna in a fire-prone system. *Biological Conservation*, 152: 212-221.

Heemstra, Simon, Bush fire patchiness, PhD thesis, School of Earth and Environmental Sciences, University of Wollongong, 2007. http://ro.uow.edu.au/theses/1

Hobbs, R. J., Currall. J. E. P. & Gimingham. C. H. (1984). The use of 'Thermocolor' pyrometers in the study of heath fire behaviour. *Journal of Ecology*, 72: 241-250.

Holland, G. J., & Bennett, A. F. (2007). Occurrence of small mammals in a fragmented landscape: the role of vegetation heterogeneity. *Wildlife Research*, 34: 387-397.

Hudak, A. T., Ottmar, R. D., Vihnanek, R. E., Brewer, N. W., Smith, A. M. S., & Morgan, P. (2013). The relationship of post-fire white ash cover to surface fuel consumption. *International Journal of Wildland Fire,* 22: 780-785.

Johnson, J. B., & Omland, C. S. (2004). Model selection in ecology and evolution. *Trends in Ecology and Evolution,* 19: 101-108.

Jurskis, V. (2005). Eucalypt decline in Australia, and a general concept of tree decline and dieback. *Forest Ecology and Management*, 215: 1-20.

Kaufmann, G. A., & Covington, W. W. (2000). Effect of prescribed burning on mortality of presettlement ponderosa pines in Grand Canyon National Park. Ft Collins, Us Dept Agr, Forest Serv Rocky Mt Forest & Range Exptl Stn.

Keane, R. E., Burgan, R., & Wagtendonk, J. V. (2001). Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire*, 10: 301-319.

Keeley, J. E. (2002). Native American impacts on fire regimes of the California coastal ranges. *Journal of Biogeography,* 29: 303-320.

Kelly, L. T., Bennett, A. F., Clarke, M. F., & McCarthy, M. A. (2014). Optimal fire histories for biodiversity conservation. *Conservation Biology*, 29: 473-481.

Knapp, E. E., & Keeley, J. E. (2006). Heterogeneity in fire severity within early season and late season prescribed burns in a mixed-conifer forest. *International Journal of Wildland Fire*, 15: 37-45.

Kocher, S. (2012). Forest fuel reduction treatments do a lot of good and not a lot of harm. Sierra Nevada Fire Science Delivery Consortium, California Fire Science Consortium and Joint Fire Sciences Program.

Leonard, S. W., Bennett, A. F., & Clarke, M. F. (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.

Liu, Z., He, H. S., Chang, Y., & Hu, Y. (2010). Analyzing the effectiveness of alternative fuel reductions of a forested landscape in Northeastern China. *Forest Ecology and Management,* 259: 1255-1261.

Maravalhas, J., & Vasconcelos, H. L. (2014). Revisiting the pyrodiversity-biodiversity hypothesis: long-term fire regimes and the structure of ant communities in a Neotropical savanna hotspot. *Journal of Applied Ecology*, 51: 1661-1668.

Mazerolle, M. J. (2004). Making sense out of Akaike's Information Criterion (AIC): its use and interpretation in model selection and inference from ecological data. World Wide Web. < http://www. theses. ulaval. ca/2004/21842/apa. html.

McCaw W.L., & Burrows N.D. (1989). Fire management. In: Dell B., Havel J.J., & Malajczuk N. (eds). The Jarrah Forest. Geobotany, vol 13. Springer, Dordrecht

McCaw, L. W., Smith, R. H., & Neal, J. E. (1997). Prescribed burning of thinning slash in regrowth stands of karri (Eucalyptus diversicolor). 1: Fire characteristics, fuel consumption and tree damage. *International Journal of Wildland Fire*, 7: 251-259.

McCaw, W. L. (2011). Characteristics of Jarrah (Eucalyptus marginata) forest at FORESTCHECK monitoring sites in south-west Western Australia: stand structure, litter, woody debris, soil and foliar nutrients. *Australian Forestry*, 74: 254-265.

McCaw, W. L. (2013). Managing forest fuels using prescribed fire - A perspective from southern Australia. *Forest Ecology and Management,* 294: 217-224.

McCaw, W. L., Gould J. S., & Cheney, N. P. (2008). Existing fire behaviour models under-predict the rate of spread of summer fires in open Jarrah (Eucalyptus marginata) forest. *Australian Forestry,* 71: 16 - 26.

McCaw, W. L., Gould, J. S., Cheney, N. P., Ellis, P. F. M., & Anderson, W. R. (2012). Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. *Forest Ecology and Management*, 271: 170-181.

McCaw, W.L., Robinson, R.M., & Williams, M.R. (2011). Integrated biodiversity monitoring for the Jarrah (Eucalyptus marginata) forest in south-west Western Australia. *Australian Forestry*, 74: 240-254.

McIver, J. D., Stephens, S. L., Agee, J. K., Barbour, J., Boerner, R. E. J., Edminster, C. B., Erickson, K. L., Farris, K. L., Fettig, C. J., Fiedler, C. E., Haase, S., Hart, S. C., Keeley, J. E., Knapp, E. E., Lehmkuhl, J. F., Moghaddas, J. J., Otrosina, W., Outcalt, K. W., Schwilk, D. W., Skinner, C. N., Waldrop, T. A., Weatherspoon, C. P., Yaussy, D, A., Youngblood, A., & Zack, S. (2013). Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study (FFS). *International Journal of Wildland Fire*, 22: 63-82.

Morgan, P., Hardy, C, C., Swetnam, T. W., Rollins, M. G., & Long, D. G. (2001). Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. *International Journal of Wildland fire*, 10: 329-342.

Mori, A. S., & Johnson, E. A. (2013). Assessing possible shifts in wildfire regimes under a changing climate in mountainous landscapes. *Forest Ecology and Management*, 310: 875-886.

Morley, S., Grant, C., Hobbs, R., & Cramer, V. (2004). Long-term impact of prescribed burning on the nutrient status and fuel loads of rehabilitated bauxite mines in Western Australia. *Forest Ecology and Management*, 190: 227-239.

Nemani, R., Pierce, L., Running, S., & Goward, S. (1993). Developing Satellite-derived Estimates of Surface Moisture Status. *Journal of Applied Meteorology*, 32: 548-557.

Neyland, M., Hickey J., Beadle, C., Bauhus, J., Davidson, N., & Edwards, L. (2009). An examination of stocking and early growth in the Warra silvicultural systems trial confirms the importance of a burnt seedbed for vigorous regeneration in *Eucalyptus obliqua* forest. *Forest Ecology and Management*, 258: 481-494.

Oliveira, S. L. J., Campagnolo, M. L., Price, O. F., Edwards, A. C., Russell-Smith, J., & Pereira, J. M. C. (2015). Ecological implications of fine-scale fire patchiness and severity in tropical savannas of northern Australia. *Fire Ecology*, 11: 10 - 31.

Parson, A., Robichaud, P. R., Lewis, S. A., Napper, C., & Clark, J. T. (2010). Field guide for mapping post-fire soil burn severity. Gen. Tech. Rep. RMRS-GTR-243. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Pasotti, M. (2014). Department of Biodiversity, Conservation and Attractions - Parks and Wildlife Service District Fire Coordinator, Perth Hills District.

Pasotti, M. (2015). Department of Biodiversity, Conservation and Attractions - Parks and Wildlife Service District Fire Coordinator, Perth Hills District.

Pasotti, M. (2017). Department of Biodiversity, Conservation and Attractions - Parks and Wildlife Service District Fire Coordinator, Perth Hills District.

Pausas, J. G., & Keeley, J. E. (2009). A Burning Story: The Role of Fire in the History of Life. *BioScience*, 59: 593-601.

Pekin, B. K., Boer. M. M., Macfarlane, C., & Grierson, P. F. (2009). Impacts of increased fire frequency and aridity on eucalypt forest structure, biomass and composition in southwest Australia. *Forest Ecology and Management*, 258: 2136-2142.

Penman, T. D., Christie, F. J., Andersen, A. N., & Bradstock, R. A. (2011). Prescribed burning: how can it work to conserve the things we value? *International Journal of Wildland Fire*, 20: 13.

Penman, T. D., Collins, L., Syphard, A. D., Keeley, J. E., & Bradstock, R. A. (2014). Influence of Fuels, Weather and the Built Environment on the Exposure of Property to Wildfire. *PLOS ONE*, 9(10): e111414.

Ponisio, L. C., Wilkin, L., M'Gonigle, L. K., Kulhanek, K., Cook, L., Thorp, R., Griswold, T., & Kremen, C. (2016). Pyrodiversity begets plant-pollinator community diversity. *Global Change Biology*, 22: 1794-1808.

Rice, K. L., Matzner, S. L., Byer, W., & Brown, J. R. (2004). Patterns of tree dieback in Queensland, Australia: the importance of drought stress and the role of resistance to cavitation. *Oecologia*, 139: 190-198.

Sitters, H., Di Stefano, J., Christie, F. J., Sunnucks, P., & York, A. (2015). Bird diversity increases after patchy prescribed fire: implications from a before–after control–impact study. *International Journal of Wildland Fire*, 24: 690 -701.

Slocum, M. G., Platt, W. J., & Cooley, H. C. (2003). Effects of Differences in Prescribed Fire Regimes on Patchiness and Intensity of Fires in Subtropical Savannas of Everglades National Park, Florida. *Restoration Ecology*, 11: 91-102.

Smith, M. A., Grant, C. D., Loneragan, W. A., & Koch, J. M. (2004). Fire management implications of fuel loads and vegetation structure in Jarrah forest restoration on bauxite mines in Western Australia. *Forest Ecology and Management*, 187: 247-266.

Sneeuwjagt, R. J., & Peet, G. B. (1985). *Forest Fire Behaviour Tables for Western Australia* (3rd ed.). Department of Conservation and Land Management.

Stephens, S. L., & Ruth, L. W. (2005). Federal forest-fire policy in the United States. *Ecological Applications*, 15: 532-542.

Stephens, S. L., Martin, R. E., & Clinton, N. E. (2007). Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *Forest Ecology and Management*, 251: 205-216.

Stephens, S. L., McIver, J. D., Boerner, R. E., Fettig, C. J., Fontaine, J. B., Hartsough, B. R., Kennedy, P. L., & Schwilk, D. W. (2012). The Effects of Forest Fuel Reduction Treatments in the United States. *BioScience*, 62: 549-560.

Taylor, R. S., Watson, S. J., Nimmo, D. G., Kelly, L. T., Bennett, A. F., & Clarke, M. F. (2012). Landscape-scale effects of fire on bird assemblages: does pyrodiversity beget biodiversity? *Diversity and Distributions*, 18: 519-529.

Tingley, M. W., Ruiz-Gutierrez, V., Wilkerson, R. L., Howell, C. A., & Siegel, R. B. (2016). Pyrodiversity promotes avian diversity over the decade following forest fire. *Royal society publishing*. DOI: 10.1098/rspb.2016.1703

Turner, M. G., Romme, W. H., Gardner, R. H., & Hargrove, W. W. (1997). Effects of fire size and pattern on early succession on Yellowstone National Park. *Ecological Monographs*, 67: 411-433.

Van Der Meer, J., & Camphuysen, C. J. (1996). Effect of observer differences on abundance estimates of seabirds from ship-based strip transect surveys. *IBIS International Journal of Avian Science*, 138: 433-437.

van der Meer, P. J., Dignan, P., & Saveneh, A. G. (1999). Effect of gap size on seedling establishment, growth and survival at three years in mountain ash (*Eucalyptus regnans* F. Muell.) forest in Victoria, Australia. *Forest Ecology and Management*, 117: 33-42.

Vellend, M., Verheyen, Kris., Flinn, K. M., Jacquemyn, H., Kolb, A., Van Calster, H., Peterken, G., Graae, B. J., Bellemare, J., Honnay, O., Brunet, J., Wulf, M., Gerhardt, F., & Hermy, M. (2007). Homogenization of forest plant communities and weakening of species-environment relationships via agricultural land use. *Journal of Ecology,* 95: 563-573.

Wardell-Johnson, G., & Horwitz, P. (2000). The recognition of heterogeneity and restricted endemism in the management of forested ecosystems in south-western Australia. *Australian Forestry,* 63: 218-225.

Westphal, M. I., Field, S. A., Tyre, A. J., Paton, D., & Possingham, H. P. (2003). Effects of landscape pattern on bird species distribution in the Mt. Lofty Ranges, South Australia. *Landscape Ecology,* 18: 413-426.

Whelan, R.J. (1995). The Ecology of Fire. Cambridge University Press, Cambridge.

White, J. D., Ryan, K. C., Key, C. C., & Running, S. W. (1996). Remote Sensing of Forest Fire Severity and Vegetation Recovery. *International Journal of Wildland Fire,* 6: 125-136.

Williams, R. J., Cook, G. D., Gill, A. M., & Moore, P. H. R. (1999). Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology*, 24: 50-59.

Wittkuhn, R. S., McCaw, L., Wills, A. J., Robinson, R., Andersen, A. N., Van Heurck, P., Farr, J., Liddelow, G., & Cranfield, R. (2011). Variation in fire interval sequences has minimal effects on species richness and composition in fire-prone landscapes of south-west Western Australia. *Forest Ecology and Management,* 261: 965-978.

Wotton, B. M., Gould, J. S., McCaw, W. L., Cheney, N. P., & Taylor, S. W. (2012). Flame temperature and residence time of fires in dry eucalypt forest. *International Journal of Wildland Fire*, 21: 270.

Xie, Y., Sha, Z., & Yu, M. (2008). Remote sensing imagery in vegetation mapping: a review. *Journal of Plant Ecology,* 1: 9-23.

Youngblood, A., Wright, C. S., Ottmar, R. D., & McIver, J. D. (2008). Changes in fuelbed characteristics and resulting fire potentials after fuel reduction treatments in dry forests of the Blue Mountains, northeastern Oregon. *Forest Ecology and Management,* 255: 3151-3169.

Appendix 1. The final field survey data sheet containing the environmental variable that predicts patchiness.

Survey 1 out of 3

Environmental variable	Total Value
Area Burnt %	

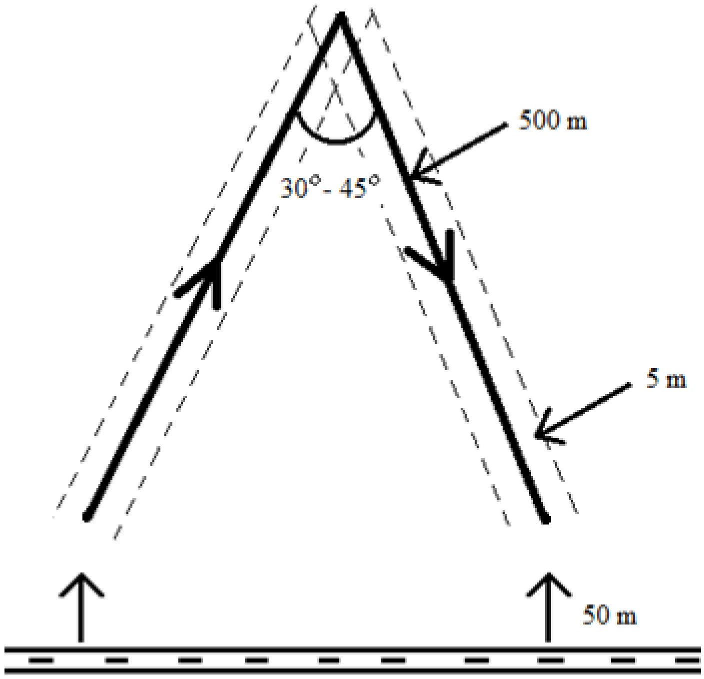


Figure 19. Field survey data sheet containing the final environmental variable, area burnt (%), that predicts patchiness. Three data sheets are required for a single post-burn assessment. The variable area burnt % will be shaded along the template image during the survey, with the distance between patches recorded. The final numbers are tallied up at the end of the survey.

Appendix 2. Variable code, name and units of measure.

Table 7. Abbreviation code, name and unit measurement of the variables used in this study.

Code	Environmental variable	Units of Measurement
HT	Habitat Trees	#
T HGT	Height of Tree	m
S HGT	Scorch Height (Leaves)	m
SLC	Scorched Leaves in Canopy	%
F HGT	Flame Height (Burnt Leaves)	m
CB HGT	Canopy base height	m
BS HGT	Bark scorch height	m
CC	Canopy cover	%
UB	Understory burnt	%
GB	Ground burnt	%
GVC	Ground vegetation cover	%
SC	Shrub cover	%
BE	Bare earth	%
LC	Litter cover	%
LD	Litter depth	cm
BCS	Basal char severity	Categorical (1-4)
AC	Ash cover	%
OE	Orange earth cover	%
BT	Branch thickness remaining [X]	< 25 mm <25 mm
MF	Month of Fire	Categorical (seasons)
FDI	Fire Danger Index (FDI)	Calculated on day of burn by Parks and Wildlife Service
SMC	Surface Moisture Content (SMC)	Calculated on day of burn by Parks and Wildlife Service
MT	Max Temperature	°C
WS	Windspeed	Km/h
VP	Veg Patches	#
AB	Area Burnt	%
TSLB	Time Since Last Burn	Years