Fuel characteristics and dynamics in shrublands of the transitional rainfall zone, Western Australia

Sarah Dalgleish

Edith Cowan University

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Fuel Characteristics and Dynamics in Shrublands of the Transitional Rainfall Zone, Western Australia.

Sarah Dalgleish

A thesis submitted in partial fulfilment of the requirements for the award of Bachelor of Science (Environmental Management) Honours

At the School of Natural Sciences, Edith Cowan University

Supervisors: Dr Eddie van Etten & Professor Will Stock

Photo: Joseph Land System (Source: S.Dalgleish 15/07/09)
Within the Mediterranean shrublands, fires are particularly intensive and widespread. In the Transitional Rainfall Zone in Western Australia, these large fires burn in areas with high conservation value, and present risks to human lives and infrastructure on properties in the region. The concern for the effect fires have on anthropocentric and ecological values in these shrublands makes it a priority in management to reduce the risks. Of the environmental and biotic factors that influence a fire, fuel is one of the most significant as it has the capacity to determine fire properties such as the intensity, extent, burn pattern within the fire, and frequency. While fuel load is the most commonly assessed parameter, there are other fuel characteristics that also contribute to the behaviour and impacts of a fire, but don’t receive as much attention. Fuel arrangement (plant density throughout the vertical profile), composition (live and dead, fine and coarse etc), continuity (horizontal distribution) and height are also important factors to consider in assessment of fuel dynamics. Knowledge on fuel dynamics provides the foundations for inferring return time of subsequent fires and the likely behaviour of these fires. For land managers, fuel characteristics may then be maintained or changed (e.g. through prescribed burning) to create a fire regime that satisfies management objectives. The purpose of this study was to gain an understanding of current fuel dynamics in shrublands of the Transitional Rainfall Zone, through assessment of fuel loading at the surface and above the ground, and assessing spatial arrangement of fuel. It was found that these shrublands had heterogeneous fuel characteristics at small spatial scales, which is typical for this type of system. Heterogeneity was more likely explained by site factors such as underlying soil differences and climate, rather than as a result of the fire itself. Senescence was a dominant feature of the system in long unburnt sites, and contributed to creation of large interpatch spaces, high amounts of suspended dead material, and litter at the surface. Recently burnt sites had
very small portions of dead material, large interpatch spaces, and litter was absent until around 14-18 years since last fire. Sites at 24-45 years since last fire had the greatest patch coverage and continuity in the horizontal and vertical array, and had larger quantities of fuel compared to all other ages. This shrubland system had slightly higher quantities of fuel than the accepted hazardous level, though it was still comparable to other similar shrubland systems in Australia and throughout the world. Patch coverage and continuity was also slightly higher than other systems, though took longer to reach this level. Equilibrium was eventually reached when sites were very old, at about 80 years since last fire. From the time shrublands in this system reach about 14 years, fuel characteristics are typical of those required to foster intensive, wide spread fires that are prevalent in this system. For management, this study has shed light on the nature of fires to be expected in this system.
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Signed

Dated 14/12/09
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1 INTRODUCTION

Fire is a recurrent feature of shrubland communities in Mediterranean climatic regions of the world (Beard et al., 1984a; Bell et al., 1984; Bond et al., 1996). Local terms used to describe shrubland ecosystems include: fynbos in South Africa, chaparral in California, maquis in Mediterranean Europe, and matorral in Chile (Beard et al., 1984b). Beard (1984b) proposed the use of the term 'kwongan' to describe this type of system in Western Australia (Beard & Pate, 1984b), where this study is located. It is said that many of the species found in these vegetation communities have been shaped by fire, and as a result have fire-promoting adaptations, or have the ability to tolerate its effects (Bond & van Wilgen, 1996). Consequentially, these adaptations (e.g. volatile oils, small leaves), coupled with the dry summers, that are a feature of Mediterranean climates, have made these systems extremely fire prone (Bell et al., 1984; Bond & van Wilgen, 1996; Keith et al., 2002).

Throughout the world, there is much apprehension over fire because of its capability to have devastating impacts on human life and property, and biodiversity (Whelan, 1995; M. A. Gill et al., 2002). Within the Mediterranean vegetation communities, fires are particularly intensive and widespread (Baeza et al., 2002; Keith et al., 2002; Keeley et al., 2009). In recent years there have been notably destructive events in this system such as the 2003 firestorms in the Californian chaparral (also recurred in 2009), which resulted in 26 lives being lost, and $US4.8 billion in damages (Keeley et al., 2006). Closer to home, in 2007 the shrublands of the Boorabin National Park near Coolgardie experienced a large wildfire which resulted in the loss of three lives. Large fires are also of concern to biodiversity because they have the potential to fragment/contract areas of long unburnt
vegetation at the landscape scale, change habitat conditions, which especially has implications for fauna, and can homogenise the landscape which can affect species that exploit patchiness (Bond & van Wilgen, 1996; Keith et al., 2002). Inappropriate fire regimes can also have negative impacts on flora and fauna, even resulting in extinction of some species (Keith et al., 2002). This can often be the case with flora when fires occur before species can establish a sufficient seed store, or when fires are not frequent enough for species that require fire to maintain recruitment (Bell et al., 1984; Bond & van Wilgen, 1996; Keith et al., 2002). The concern for the effect fires have makes it a priority in management to reduce the risks, and subsequently protect these anthropocentric and ecological values. To do this successfully, understanding of the fundamental components of fire behaviour and how it can be manipulated is required (Whelan, 1995; Keith et al., 2002).

Of the environmental and biotic factors that affect a fire, fuel is one of the most significant as it has the capacity to determine fire properties such as the intensity, extent, burn pattern within the fire, and frequency (Luke et al., 1978; Whelan, 1995; Hodgkinson, 2002; Catchpole, 2002). Fuel is often defined as anything that is susceptible to ignition and combustion. In this study the term fuel refers to above ground vegetation as only this form is present for burning (Luke & McArthur, 1978; Chandler et al., 1983; Burrows, 1990). Identifying the temporal and spatial dynamics of fuel allows managers to predict the occurrence and behaviour of planned and current fires, or strategically influence those fires through maintenance of fuel characteristics (e.g. through prescribed burning) (Luke & McArthur, 1978; Chandler et al., 1983; Myers et al., 2007).

In studies, fuel load (net build up of combustible biomass over time) is the most commonly assessed parameter because it is a fundamental determinant of fire intensity and is used in many models to predict impacts of fire (Pluckinski, 2003). Fuel load is often
only assessed at ground level. This is mostly the case in forests, as litter at ground level generally sustains fires in this system (McCarthy, 2004). In other systems such as Mediterranean shrubland communities, fuel is distributed throughout the profile, with live and dead aerial vegetation constituting the bulk of fuel, while litter contribution is small; thus in this system fires usually burn above ground consuming the vertical fuel array (Bradstock et al., 1993; Pluckinski, 2003; Baeza et al., 2006; Keeley et al., 2008). Not all vegetation will reach complete combustion, the fine fraction of fuel load represents 'available' fuel, while most biomass is 'potential' fuel, and may only achieve combustion in certain circumstances (Luke & McArthur, 1978; Whelan, 1995). Total biomass is not considered to be potential fuel because it may comprise large stems that will not be consumed in all fires (Chandler et al., 1983). However in some cases when these stems are killed in the fire they can contribute to loading in subsequent fires (Chandler et al., 1983). It should also be noted that fuel in this study is not considered to be biomass as this term incorporates plant roots and animal matter, instead the term phytomass will be used when referring to fuel quantity as it represents all plant material above the mineral soil (Chandler et al., 1983).

Compared to forests, patterns of fuel accumulation in Mediterranean systems is also thought to be much more complex, due to localised site differences, climatic variables, and pyric succession (i.e. changes in dominant shrub species; Plucinski, 2003). Consequently, the distribution of fuel load can be highly variable with fuels going from continuous to discontinuous over small areas which affects the burn pattern of a fire (Catchpole, 2002). The effect on the burn pattern feeds back into the vegetation, and subsequently contributes to the heterogeneity that is characteristic of this system (Bond & van Wilgen, 1996; Catchpole, 2002; Keith et al., 2002). The complexity in shrubland communities highlights
the importance of incorporating both standing phytomass and ground litter at various spatial scales when sampling fuel in this system.

However, while fuel load is important, there are other fuel characteristics that also contribute to the behaviour and impacts of a fire, but do not receive as much attention. Fuel arrangement (plant density throughout the vertical profile), composition (live and dead, fine and coarse etc), continuity (horizontal distribution) and height are also important factors to consider in assessment of fuel dynamics (Bradstock & Gill, 1993; Bond & van Wilgen, 1996; Pluckinski, 2003; Schwilk, 2003; Baeza et al., 2006).

In Mediterranean shrubland communities in the Transitional Rainfall Zone (TRZ), Western Australia, fires are intensive, widespread and relatively frequent (mostly caused by lightning). At Charles Darwin Reserve (CDR), a conservation property in the northern portion of the TRZ, wildfires occur about every three years and burn predominantly in these shrubland communities (Braun, n.d.). The intensive fire behaviour in shrublands is largely attributed to suspension of available fuel throughout the profile which is well aerated and has a low moisture content (Keith et al., 2002; Baeza et al., 2002). Braun (2006) observed fire behaviour in shrublands on the CDR property in relation to fuel arrangement, and how this influenced the way fire travelled through the vertical profile. In accordance with general fire behaviour in shrublands, it was noticed that the fires consumed suspended fuel and lower branches of plants, and heat released from consumption of fuels in this layer resulted in crown fires (Braun, 2006). While this arrangement and vertical continuity is important for development of a fire from the ground to the crown, horizontal continuity facilitates spread of a fire through the landscape. As can be seen from the example of fire development at CDR, the locality of horizontal continuity of fuel in the profile need not always be at the ground levels. Development of a ground fuel layer in shrubland communities is usually insufficient to carry a fire as most of the plants
that constitute this system retain their dead foliage (Keith et al., 2002). With most of the fuel being located above the ground, fire spreads through the landscape via continuous fuel in the upper levels and crown (Bond & van Wilgen; 1996; Myers et al., 2007). Understanding fuel dynamics in vegetation communities provides land managers with a means to control fires to meet their specific management objectives. In shrubland communities, understanding fuel characteristics presents an interesting challenge due to the complicated nature of fuel development in these systems. Even more of a challenge though is development of appropriate fire regimes for areas that have integrated vegetation communities with disparate fire requirements (Specht, 1979; Keith et al., 2002; Lullfitz et al., 2008).

The aforementioned Transitional Rainfall Zone in Western Australia (Hopper, 1979), is one system that contains a mosaic of vegetation communities where appropriate fire management is essential to preserve the high conservation value of the area (Beard et al., 2000). Experiencing between 300-400 mm of annual rainfall, this area is the transitional zone between the high-rainfall of the southwest and the arid interior (Hopper, 1979). As a result the area contains a large number of endemic flora species, and is highly diverse (Hopper, 1979). Studies have found the number of species in this transitional zone to be much greater than the number of species in the adjacent rainfall zones (Hopper, 1979). It is thought that the high endemism is a result of historical climatic pulses between wet and dry conditions over the Quaternary Period which facilitated evolution of many new taxa combined with relatively low extinction rates (Hopper, 1979; Sattler et al., 2002; Hopper et al., 2004).
In the part of the TRZ where Charles Darwin Reserve is situated there are 16 major vegetation communities (land systems), which are classified according to the topography and soil as well as the species they comprise (Braun, 2006). While some land systems are extremely flammable (e.g. lateritic shrublands, sandplain shrublands), not all these land systems are fire prone and some are even quite fire sensitive (e.g. York gum and Salmon gum woodlands; Braun, 2006). The woodlands, and other systems such as the lakes system and greenstone hills system, act as natural fire breaks. At boundaries with these systems fire rarely ventures beyond the edge of these patches before being extinguished, as the fuel is sparse and patchy (Braun, 2006). One of the land systems is of interest as it comprises a particularly flammable array of species that support large, intensive wildfires. This land system, known as the Joseph Land System, is characterised by extensive sandplain shrublands that cover about 50% of the 68,000 ha property (Braun, 2006). This land system is also the most predominant in the Transitional Rainfall Zone. Documentation of fire events since 1969 across CDR has shed light on the frequency and extent of fires in this land system. These historical records have shown that between 1969 and 2004, 88% of the burnt area on the CDR property was by fires confined to this Joseph Land System (Braun, 2006). While fires have been prevalent, 31% of this land system has not been burned since the 1960s, and the ecological significance of these long unburnt areas is largely unknown.

Research in heathlands, a similar system to these shrublands, has claimed that some species require fire within a specific time interval for regeneration otherwise they will be eliminated from the system (Specht, 1981; Pluckinski, 2003; Braun, 2006). Equally if fire is too frequent then other species may become locally extinct (Moritz et al., 2004; Braun, 2006). To follow on, there are many other land systems intermixed with the Joseph Land System such as the York Gum (E. loxophleba) Woodlands, that are known to be sensitive
to fire (Hollenbach, 2008). Studies on these York Gum (E. loxophleba) Woodlands found that older trees were killed outright by fire, however there was mass recruitment following this event (Hollenbach, 2008). Vegetation response to fire in this system provides one example of how fire frequency could have negative impacts, as it was recognised that where fire is too frequent, it does not allow for seed banks to build up enough for successful regeneration (Hollenbach, 2008).

At Charles Darwin Reserve and other nearby properties, it is a major challenge for the local fire fighters to control and extinguish the large and extensive wildfires (Braun, n.d.). Historical management of fires on the property was to let the large wildfires burn themselves out, though in recent year’s fire suppression strategies, such as back burning, have been put in place (Braun, n.d.). These large, recurring wildfires present concerns for managers pertaining to development of appropriate fire regimes that are also manageable to maintain the unique floristic and faunal composition of the land systems in the area. Furthermore these fire events present significant risks to human life, property and values at Charles Darwin Reserve and nearby properties that contain large areas of the highly flammable shrublands. To work towards conservation efforts for vegetation communities in the region, an established knowledge base on fuel dynamics will assist pre-fire planning or if a wildfire was to flare up, help fire-fighters to efficiently manage the event.

Apart from the studies conducted by Braun (2006) on fire behaviour and management, and Hollenbach (2008) on fire ecology of eucalypts, studies carried out near Charles Darwin Reserve, and in the broader Transitional Rainfall Zone, are limited to fire threats to fauna (Parsons, 2008) and mapping of fire scars and modelling of fuel levels in the Lake Johnston region, approximately 500 km from CDR, (O'Donnell et al., 2007). So far there have been no studies on the fuel dynamics in this region. Heathlands, being the closest well studied analogue (Keith et al., 2002), may therefore be a suitable system to observe
possible floristic responses to fire, and to compare subsequent effects on fuel dynamics. However, little is also known about fuel dynamics, especially the arrangement and composition of fuel, in these shrublands across Australia and internationally. Because of the lack of research into these systems, there is also an absence of appropriate techniques to sample fuel to capture the complexity of the fuel characteristics.

Where assessment of above-ground biomass has been made, the most common approach has been large phytomass removal (e.g. whole plants) because it provides the most accurate measure of fuel load (Catchpole et al., 1992). This is not always desirable, especially in conservation areas as significant amounts of vegetation may be removed. This method also does not always allow for quantification of fuel at various levels throughout the profile, and observed nature of fires in these systems indicates this could be valuable data to predict fire behaviour. Overcoming the need to sample large amounts of phytomass, and being able to quantify fuel at different levels in profile was one priority in this study. Methods need to be explored that require only small amounts of phytomass be removed and if possible eliminate the need to remove biomass altogether, which could possibly be achieved by exploring relationships between biomass and vegetation density measures.

Information on fuel dynamics in the sandplain shrublands of the Transitional Rainfall Zone, is of considerable interest to Bush Heritage Australia (BHA; managers of CDR), Australian Wildlife Conservancy (AWC; managers of adjoining Mount Gibson Wildlife Sanctuary), and the Department of Environment and Conservation (DEC) who are responsible for fire management on the large areas of unallocated crown land adjoining these reserves. This knowledge will provide the foundations for inferring return time of subsequent fires and the likely behaviour of these fires in patches of various post-fire ages.
For land managers, fuel characteristics may then be maintained or changed (e.g. through prescribed burning) to create a fire regime that satisfies management objectives.

In light of the important role of fuel in successful fire management, this study aims to assess fuel characteristics, of both ground litter and standing biomass, across sites of varying post-fire ages to understand the nature of fuel accumulation and arrangement in sandplain shrublands of the Transitional Rainfall Zone. Specifically the following objectives identify features of fuel characteristics that are of most interest to achieve this broad aim and these include:

1. An assessment of surface and above ground fuel loading, type, and distribution

2. Quantification of the spatial continuity of fuels at local scales.

3. An assessment of the density and arrangement of fuel types in the vertical profile

4. Determining the relationship between density and quantity measures to investigate whether density can be used as a surrogate for predicting fuel load.
2 METHODS

2.1 Description of Study Area

Location

The study is located in the northern portion of the Southwest Botanical Province, Western Australia. Sampling was carried out on two conservation reserves in the area: Charles Darwin Reserve (CDR), which was formerly White Wells Pastoral Station, and Mt Gibson Wildlife Sanctuary (MGWS). The properties are bisected by the Great Northern Highway, and are situated about 80km northeast of Wubin and 350km northeast of Perth (Fig 2.1).

Figure 2.1. Location of study area in relation to regional centres in Western Australia.
Vegetation

A survey on the Sandstone-Yalgoo-Paynes Find area, where the properties reside, found 706 native vascular species with 66 being listed as declared rare flora and priority flora (Payne et al., 1998). Vegetation comprises a mosaic of recurring vegetation units, and there are 15 land-systems in the study area, which are characterised by their vegetation, landforms, drainage patterns, and soils. The Joseph land system, which was selected for this study, supports dense mixed shrubs comprising Acacia, Melaleuca, Allocasuarina and Hakea (Payne et al., 1998). It is the most widespread land-system in the study area, and is fire-prone. Beard (1976) mapped this vegetation as “Acacia thickets on sandplains”.

Climate

The study area lies within the ‘Extra Dry Mediterranean’ and the ‘Semi-desert Mediterranean’ bioclimatic regions (Beard, 1982). These climatic zones constitute the Interzone below the 300-250 mm isohyets, and experience between 7-11 dry months annually (Beard, 1982). Rainfall in this region has relatively high inter-annual variability and the area often suffers drought (recent droughts were experienced in 2000, 2001, 2002, 2005 and 2006). Refer to appendix I for historical annual rainfall charts.

Geology, topography, and soils

Within the Sandstone-Yalgoo-Paynes Find area, twelve broad soil groups have been identified (Payne et al., 1998). The most widespread soil type is sand overlying sandplains and granitic areas, and deep red earth (Payne et al., 1998). The Joseph land system is characterised by undulating deep yellow sandplains, and in terms of geological formation comprises Cainozoic alluvial and colluvial sand deposits, and minor Archaean granite (Payne et al., 1998). Areas of sandplain that are lower in the landscape receive diffuse
runoff and comprise ironstone gravel mantles (Payne et al., 1998). Granite outcrops are also a feature in this system, however they are quite small in extent and widely dispersed (Payne et al., 1998).

2.2 Site Selection

Fifteen sites of various post fire ages were selected within the Joseph land-system. Sites were assigned to one of five age classes, and each age class contained three sites (or replicates). Ages were identified from ‘fire scar’ maps derived from satellite imagery and aerial photos by the DEC that were validated and corrected by Braun (2006) and then Parsons (2008). Since the exact year and month of a burn is not known for many of the fires, age classes were based on the year fire scar imagery was collected. The post-fire age could only be speculated for sites burnt before 1969, as this is the limit of historical fire records. To validate the estimated post-fire age of these particular sites, field-based observations were made such as the presence of fence posts (made from Callitris) from c.1920s, which would have been destroyed had there been a fire. The age classes established were selected to incorporate significant post-fire regeneration phases and subsequently facilitate comparisons between key ages (Plate 2.1). Refer to Table 2.1 for age classes and their respective sites.
Table 2.1. Details of selected post-fire ages in relation to the year images were obtained with corresponding post fire age range in which fire burned.

<table>
<thead>
<tr>
<th>Age Class (yrs)</th>
<th>Imagery Year</th>
<th>Field I.D.</th>
<th>Inferred post fire age range (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;7</td>
<td>2002</td>
<td>4A</td>
<td>7-8</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>4B</td>
<td>7-8</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>4C</td>
<td>7-8</td>
</tr>
<tr>
<td>8-11</td>
<td>2001</td>
<td>3A</td>
<td>8-9</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>3B</td>
<td>9-11</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>3C</td>
<td>9-11</td>
</tr>
<tr>
<td>14-18</td>
<td>1995</td>
<td>1A</td>
<td>14-17</td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td>1C</td>
<td>14-17</td>
</tr>
<tr>
<td></td>
<td>1992</td>
<td>1B</td>
<td>17-18</td>
</tr>
<tr>
<td>24-40</td>
<td>1985</td>
<td>2C</td>
<td>24-29</td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>2B</td>
<td>32-37</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td>2A</td>
<td>40-45</td>
</tr>
<tr>
<td>&gt;40</td>
<td>40++</td>
<td>5A</td>
<td>45-60</td>
</tr>
<tr>
<td></td>
<td>40++</td>
<td>5B</td>
<td>60-80+</td>
</tr>
<tr>
<td></td>
<td>40++</td>
<td>5C</td>
<td>60-80+</td>
</tr>
</tbody>
</table>

Sites were confined to deep yellow sandy soil of the Joseph Land System, and avoided edge effects such as breakaways, boundaries with other land-systems or fire ages, obvious soil differences, and road edges, to minimise the influence of environmental factors adding to site variability. The choice of areas for sites was further limited to areas that could be reached via access tracks on the properties, and public roads.

Pseudo-replication is an important issue for site selection since there is the potential for sites to be within the same treatment (fire). To minimise this issue sites were located in distinct fire scars or, if this was not possible (e.g. for large fire scars), spatially separated to incorporate variation within a single fire scar. Figure 2.2 shows the location of sites on both properties.
Figure 2.2. Site localities at the regional scale with fire scar and Joseph Land System layers. Note: Fire scar dates denote the year imagery was taken, not necessarily the year the fire occurred.
Plate 2.1. Examples of three regeneration phases after fire in the Joseph Land System; a.) Long unburnt >40 years since last burn, b.) 14-17 years since last burn and, c.) 7-9 years since last burn. (Source: S.Dalgleish 15/08/09)
2.3 Sampling Design and Method

This study used a space-for-time approach since the intent was to examine the change in variables pertaining to fuel dynamics over long periods of time (>50 years).

Within the 5 age classes the 15 sites were sampled with three 20m line transects; the transect locations were randomly chosen and separated from each other by a minimum of 20 metres. Transects were run in a north to south direction. Three transects for each site was chosen because preliminary field trials indicated this number would be sufficient to sample site variability.

Fuel was measured by dividing it into four categories; live fine, live coarse, dead fine, and dead coarse. Fine fuel was defined as combustible material up to 10mm diameter.

Assessment of vertical arrangement

To assess the vertical arrangement and density of fuel, a modified Levy pole method was used (Smith et al., 2004). In this method a rod marked at 25cm intervals was held vertically and the number of vegetation intercepts within each interval on the rod counted and recorded. Each intercept was assigned to one of the four fuel categories (Plate 2.2). Measurements were taken at a horizontal intervals of 25cm, and 81 points along each transect were assessed.
Plate 2.2. Measuring fuel density using the pole intercept technique. The number of vegetation intercepts with the pole in each 25cm interval were counted and recorded according to the pre-determined fuel categories. (Source: S. Dalgleish 15/08/09)

Assessment of spatial continuity

Spatial continuity of fuel was assessed through measuring litter depth and patch size. At each 25cm point where vertical arrangement was assessed, the depth (mm) of litter was recorded. Patch and interpatch size was calculated by obtaining the sum of intercepts at each sampling point from the above methods, and counting the number of 25cm intervals with and without any intercepts recorded. Intervals that had a sum of intercepts of ≤2 and were isolated (i.e. in the middle of an interpatch) were counted as interpatch.

Quantification of fuel

To quantify fuel, samples of standing phytomass at various heights in the profile and litter on the ground were collected, since both are important fuel characteristics that affect the behaviour of a fire in shrubland ecosystem. To overcome the need for large biomass
removal, a method was devised that required removal of much smaller quantities, and allowed for material to be collected at various height intervals. With this method a 0.0156 m$^3$ open sided cube was attached to a pole calibrated at 25 cm intervals (to a height of 4 m; Plate 2.3). Collection of phytomass entailed a stratified random sampling approach; points for collection were contained within patches (since interpatches, by definition, had no or little vegetation). Sampling points were selected, and samples obtained, at points along transects that best represented the fuel array of the overall site. Samples were obtained by placing the cube so the sampling point (coordinated with point that intercept measurements were made) was at the centre (i.e. 12.5 cm to all edges of the cube). All plant material was removed from within the cube using secateurs, at each 25 cm vertical interval (intervals correspond to intervals used in intercept method) from the ground to the crown. Material was sorted into the aforementioned fuel categories and weighed. Litter was then dried at 80°C for 4 days before being weighed. Fifteen points (along transects) were planned to be sampled as a minimum at each site, but sampling difficulties at some sites only allowed for 11 samples to be collected.

Plate 2.3. Collection of fuel to assess quantities at each level. Fuel was removed from within the frame, and was bagged for drying and weighing. (Source: S.Dalgleish 15/08/09)
2.4 Data Analysis

Calculating means for each site

Mean sum of phytomass for live fine, dead fine, and total fine fuel, was calculated by summing the fuel loading in each column sampled (all vertical intervals added together) and obtaining a mean of these sums at each site. These values were standardised by converting measurements from 0.0625 g m\(^{-2}\) to g m\(^{-2}\), (i.e. multiplied by 16) to obtain a measure of fuel within a patch, or were multiplied by the percentage of patch area at the site (and by 16) to get a fuel value (g m\(^{-2}\)) that represents the whole site. Mean sum of intercepts was calculated similarly to the mean sum of phytomass, where the sum of intercepts was obtained at each sampling point and averaged across the number of sampling points (n = 81 X 3 for each site). A measure of patch variability was obtained for each site by calculating the mean standard deviation of patch size and finding the mean of these values across sites.

Analysis of Variance (ANOVA)

To address objective one, one-way Analysis of Variance was performed using SPSS v.17 to test for differences in means of each fuel variable between age classes. This was done using site means as calculated above (i.e. n=3 for each age class). Fuel variables were: patch and interpatch measures (size, ratio, percentage, and variability), available standing fuel quantities (live fine, dead fine, and total), and litter (mass and depth). Percentage patch was transformed using the Arcsin transformation before testing. To test which age classes were different for variables with significant differences, the Tukey’s b post-hoc test was used.
Regression analysis (linear and non-linear) was used to explore relationships between phytomass and fuel density using SigmaPlot v.10. Regressions were performed with various degrees of averaging (i.e. firstly with raw data, then mean value across transects, mean value of sites, and mean values per age classes) to explore the effect averaging had on the strength and significance of relationships. Regressions were also used to explore relationships between fuel loading and time since last fire (objective 1). Values used in regressions included; Mean sum of intercepts and phytomass for each vertical interval, which was calculated by finding the mean of raw values at each vertical interval, for each site. These values were used to calculate the mean at each vertical interval for the age classes. In results where ‘intercepts corresponding to phytomass’ is referred to, the values used were limited to those at the same point along the transect that phytomass was collected from. This was used to explore whether phytomass immediately corresponded to the density measurements.
3 RESULTS

3.1 Assessment of surface and above ground fuel loading, type, and distribution

*Fine fuel loading across age classes*

Mean total fine (<10mm diameter) fuel load (g m\(^{-2}\)) is similar from age class <7 until 14-18 years. Thereafter loads increase until peaking at age class 24-40 (Fig 3.1). Fuel load then generally declines at sites not burnt for at least 40 years (Fig 3.1). Mean live fine standing fuel across the sites decreased slightly in the 8-11 age class and increased thereafter until declining again when post fire age exceeds 40 years. Mean dead standing fine fuel increased until the 24-40 age class and then declined (Fig 3.1). Despite these trends in mean fuel levels at the aforementioned age classes, a one-way ANOVA showed no significant (P<0.05) differences in total, live fine and dead fine standing fuel loading between age classes (Table 3.1). Litter load and depth increased gradually with time since last fire until the >40 age class where litter depth declined whilst litter mass continued to increase (Table 3.1). Litter mass ranged from no litter for sites in the <7 age class to approximately 666 g/m\(^2\) in sites in the >40 age class (Table 3.1). A one-way ANOVA demonstrated significant differences in litter mass between age classes (F = 3.38, p = 0.05), whilst there was no significant difference in litter depth between age classes (Table 3.1). Post-hoc tests found age class 24-40 years to be different to the <7 years age class. The >40 age class was also different to the 8-11 and <7 age classes (Table 3.1).
Figure 3.1. Estimated contribution of litter, live fine and dead fine fuel to total fuel loading (g m$^{-2}$) across age classes.
Table 3.1. Mean (± SE) of fuel characteristics for each age class and results of one way ANOVA testing differences between means. Values with the same letter indicate they weren’t significantly different from each other.

<table>
<thead>
<tr>
<th></th>
<th>Age class (years)</th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;7</td>
<td>8-11</td>
<td>14-18</td>
<td>24-40</td>
<td>&gt;40</td>
</tr>
<tr>
<td>Patch size (m)</td>
<td>1.00 ± 0.02</td>
<td>1.17 ± 0.16</td>
<td>1.25 ± 0.17</td>
<td>2.42 ± 0.70</td>
<td>3.92 ± 1.57</td>
</tr>
<tr>
<td>Interpatch size (m)</td>
<td>0.69 ± 0.08</td>
<td>0.86 ± 0.27</td>
<td>0.63 ± 0.06</td>
<td>0.38 ± 0.05</td>
<td>0.72 ± 0.07</td>
</tr>
<tr>
<td>% Patch cover</td>
<td>59.5 ± 3.4(^b)</td>
<td>58.7 ± 8.9(^b)</td>
<td>66.1 ± 5.0(^c)</td>
<td>84.2 ± 4.6(^a)</td>
<td>81.8 ± 3.7(^e)</td>
</tr>
<tr>
<td>Patch/interpatch ratio</td>
<td>1.45 ± 0.21</td>
<td>1.36 ± 0.72</td>
<td>1.98 ± 0.50</td>
<td>6.37 ± 3.05</td>
<td>5.44 ± 1.58</td>
</tr>
<tr>
<td>Patch size variability</td>
<td>0.61 ± 0.02(^a)</td>
<td>1.00 ± 0.14(^a)</td>
<td>0.88 ± 0.13(^a)</td>
<td>2.09 ± 0.57(^b)</td>
<td>2.38 ± 0.47(^b)</td>
</tr>
<tr>
<td>Live fine(^1) phytomass (g m(^{-2})) per area</td>
<td>1219 ± 497</td>
<td>994 ± 433</td>
<td>1107 ± 163</td>
<td>1855 ± 295</td>
<td>1547 ± 243</td>
</tr>
<tr>
<td>Live fine(^1) phytomass (g m(^{-2})) within patch</td>
<td>2011 ± 740</td>
<td>1579 ± 459</td>
<td>1701 ± 286</td>
<td>2214 ± 385</td>
<td>1880 ± 249</td>
</tr>
<tr>
<td>Dead fine(^1) phytomass (g m(^{-2})) per area</td>
<td>115 ± 75</td>
<td>153 ± 17</td>
<td>174 ± 74</td>
<td>536 ± 219</td>
<td>342 ± 60</td>
</tr>
<tr>
<td>Dead fine(^1) phytomass (g m(^{-2})) within patch</td>
<td>200 ± 125</td>
<td>275 ± 59</td>
<td>249 ± 95</td>
<td>652 ± 270</td>
<td>419 ± 77</td>
</tr>
<tr>
<td>Total fine(^1) fuel portion of phytomass (g m(^{-2})) per area</td>
<td>1235 ± 499</td>
<td>1068 ± 443</td>
<td>1207 ± 185</td>
<td>2185 ± 241</td>
<td>1857 ± 313</td>
</tr>
<tr>
<td>Total fine(^1) fuel portion of phytomass (g m(^{-2})) within patch</td>
<td>2041 ± 750</td>
<td>1705 ± 458</td>
<td>1844 ± 303</td>
<td>2617 ± 370</td>
<td>2259 ± 343</td>
</tr>
<tr>
<td>Litter depth (cm)</td>
<td>0.25 ± 0.08</td>
<td>0.31 ± 0.02</td>
<td>0.40 ± 0.08</td>
<td>0.45 ± 0.09</td>
<td>0.37 ± 0.03</td>
</tr>
<tr>
<td>Fine litter mass (g m(^{-2})) per area</td>
<td>0.00(^a)</td>
<td>146 ± 100(^w)</td>
<td>293 ± 196(^b)</td>
<td>496 ± 73(^b)</td>
<td>666 ± 226(^b)</td>
</tr>
<tr>
<td>Fine litter mass (g m(^{-2})) within patch</td>
<td>0.00</td>
<td>221 ± 128</td>
<td>464 ± 300</td>
<td>600 ± 117</td>
<td>794 ± 231</td>
</tr>
</tbody>
</table>

\(^1\) Fine fuel is defined by phytomass ≤10mm diam.
Vegetation structure and quantity

The vertical distribution of mean phytomass (g 0.156 m$^{-3}$) shows the location and quantity of fuel throughout the profile with increasing time since last fire and, increasing vegetation height (Fig 3.2). At the <7 and 8-11 age classes, the bulk of live and dead fine fuel is located 0-50cm from the ground and reduces proportionately as height above the ground increases (Fig 3.2). In contrast, most live fine fuel mass occurs between 25cm-1m for the age class 14-18, while the dead fine portion of fuel is concentrated at ground level (0-25cm) (Fig 3.2). At sites in the 24-40 age class, the bulk of live and dead fine fuel is located again at ground level (Fig 3.2). In the >40 age class the live fine fuel bulk is distributed at three points in the vertical profile: at the ground (0-25cm) level, middle (1.75-2m), and crown (3-3.50m) (Fig 3.2). These older sites display significantly less fine fuel quantity compared to younger sites, and contain a very small amount of fine fuel between 25 -75cm and 2.25-2.75cm. Dead fine fuel in the >40 age class was also much less than sites with more recent burns, however the distribution of this fuel type was more continuous and was present at all levels in the profile (from 0-4m). While mean trends are of interest, it should also be noted that age classes show large variation between sites, with the standard error often exceeding the mean fuel values; this was especially the case in live fine fuels (Fig 3.2).
Figure 3.2. Vertical distribution of live fine and dead fine fuel mass for each age class (+/- SE; n = 3)
Fine fuel loading with time since last fire

There was little or no relationship between total or live fine fuel and time since last fire, (total fine fuel linear \( r^2 = 0.11 \) and quadratic \( r^2 = 0.12 \); live fine linear \( r^2 = 0.03 \) and quadratic \( r^2 = 0.03 \); Fig 3.3). There was a relationship between dead fine fuel and time since last fire with a quadratic fit \( r^2 \) of 0.26, and a linear fit \( r^2 \) of 0.14. Sites that have post fire burn ages of up to 10 years show extremely large variability in live fine fuel within sites (Fig 3.3). In particular, one site with a post fire burnt age of 7-8 years had much greater intra-site variability compared to variability within two other sites of the same age (Fig 3.3).
Figure 3.3. Mean (± SE) standing fuel load with time for total fine standing fuel, dead fine and live fine fuel load.
3.2 Quantification of spatial continuity

*Spatial continuity*

Mean patch size increased with time since last fire, as did the patch/interpatch ratio (Table 3.1). Mean patch size started at 1.0 m in the <7 age class and increased up to 3.9 m in the >40 age class (Table 3.1). In contrast, mean interpatch size varied across all sites and displayed no clear trend in relation to increasing age (Table 3.1). Age class 8-11 years had the largest mean interpatch size at 0.86 m (Table 3.1). The >40 age class had a mean interpatch size of 0.72 m while the 24-40 had the smallest at 0.38 m (Table 3.1).

One way ANOVA tests indicated there were no significant (P>0.05) differences between age classes for mean patch size, interpatch size, and patch/interpatch ratio (Table 3.1). Patch variability was greatest in very long unburnt sites ranging from 24 to >40 years since last burn (Table 3.1). A one way ANOVA test indicated significant differences between age classes for mean patch size variability (F = 5.34, p = 0.01; Table 3.1). Post-hoc tests found the >40 and 24-40 age significantly greater patch variability to the <7, 8-11 and 14-18 age classes. The percentage patch cover increased with time since last fire (Table 3.1). The largest percentages of patch cover were in the 24-40 and >40 age classes and the least coverage was in the <7 and 8-11 age classes (Table 3.1). A one way ANOVA shows there was a significant (P<0.05) difference in percentage patch cover between age classes (Table 3.1). Results from post hoc test found the age classes 24-40 and >40 year were significantly greater than the 8-11 and <7 age classes. The age class 24-40 was also greater than the 14-18 age class (Table 1).

Within sites, there was little patch size variability for sites in the age classes <7, 8-11 and 14-18 years (Fig 3.4). Site C (burnt between 24-29 years ago, imagery date 1985) in the age class 24-40 had greater inter-site variability compared to the other two sites in the
same age class (Fig 3.4). In the >40 age class, site C (burnt 60-80+ years ago) had considerable inter-site variability (Fig 3.4).

Figure 3.4. Mean patch size (+/- Std-deviation) of sites within each age class.

**Fuel arrangement profile**

The profile diagram displays a cross sectional view of vertical and horizontal fuel continuity (Fig 3.5). Transects presented are representative of the age class and were selected because the raw values of these transects were similar to the calculated mean for their respective age class. In these diagrams the changing vegetation structure across the various post fire ages can be visualised, with the youngest sites (from the <7 and 8-11 age classes) having considerable interpatch space in relation to patch, and low vegetation at <1.25 m high. In the 14-18 and 24-40 age classes the vegetation is much taller with the upper limit between 2-2.50m and there is minimal interpatch space making it relatively
continuous spatially (Fig 3.5). In the <40 age class the vegetation height reaches 4m and while patch covers a considerable portion of the transect, the interpatch space also increases (Fig 3.5), with a gap of almost 3 m quite clearly shown. The change in understory fuel array and development of understory space can also be observed. In the age classes <7 and 8-11 there is very minimal open space within patches. For the age classes 14-18 and 24-40, understory space within patch begins to feature until the >40 age class where it is established and large spaces beneath the canopy can be observed. In the >40 age class most of the fuel is concentrated in the crown and the shrub layer up to 25 cm from the ground while in the 14-18 and 24-40 age classes fuel is still continuous in parts from the ground to the crown. (Fig 3.5).
Figure 3.5. Example of cross-section of fuel array for each age class. Dark green areas indicate where fuel is present while light green is where fuel is absent.
3.3 Assess density and arrangement of fuel types in the vertical profile

*Vegetation Density across age classes*

The age classes <7 and 8-11 show both live and dead fine fuel density (as measured using Levy pole intercepts) is concentrated between 0-50 cm from the ground and becomes less complex at higher levels (Fig 3.6). In the age class 14-18 the density of live fine fuel was greatest at 50-75 cm from the ground while dead fine fuel remained concentrated at 0-25 cm (Fig 3.6). The age class 24-40 years had the most continuous density of live and dead fine fuel with the live fine fuel establishing a complex array from 0-1.50 m (Fig 3.6). A substantial dead fine fuel array was concentrated at 0-25cm in this age class and proportionately decreased up until 2.50 m off the ground (Fig 3.6). In the >40 age class live fine complexity was established in a shrub layer 0-25cm from the ground and decreased hereafter until 2m where the crown becomes established and is continuous up until 4 m (Fig 3.6). Dead fine fuel in the >40 age class is continuous from the ground to 4m though the most considerable complexity is in the interval from 0-25cm from the ground (Fig 3.6). Density results for each site are shown in appendix II.
Figure 3.6. Vertical distribution of mean (+SE) live and dead fine fuel density for each age class.
3.4 Exploration of relationships between density and quantity measures

**Relationship between fuel quantity and density across age classes**

Linear regression analysis between the raw values for the sum of phytomass and corresponding intercepts within each sampling column across all sites, found there was no relationship ($r^2 = 0.08$, $p < 0.0001$). When regression analyses was conducted for each age class separately, no relationship was found for any of the age classes except the <7 age class which registered a modest relationship between summed intercepts and phytomass ($r^2 = 0.50$, $p = 0.0002$; Fig 3.7).

When regression was used to explore the relationship between mean phytomass and mean number of site intercepts for each 25 cm vertical interval averaged across the entire age class, age classes 24-40, 8-11, and <7 showed significant relationships with $p = 0.005$, 0.0004, and 0.03 respectively. Age classes 24-40 and <7 showed strong relationships with $r^2 = 0.69$ for 24-40, and $r^2 = 0.63$ for <7. The 8-11 age class showed a very strong relationship with $r^2 = 0.97$. While the 14-18 age class showed a strong relationship with $r^2 = 0.52$, this relationship wasn't significant, $p = 0.11$. The >40 age class showed no relationship with $r^2 = 0.15$ and this it wasn’t significant $p = 0.39$ (Fig 3.8).

When linear regression was used to explore the relationship between mean phytomass and mean number of intercepts at corresponding sampling points at each vertical 25 cm interval, two age classes registered a very strong relationship: the 8-11 ($r^2 = 0.98$) and 14-18 ($r^2 = 0.91$) (Fig 3.9). Both of the relationships were significant with $p = 0.003$ for 8-11 and $p = 0.0004$ for 14-18. The >40 year age class also registered a strong relationship ($r^2 = 0.58$) and this relationship was also significant as $p = 0.0006$ (Fig 3.9). When mean phytomass was regressed against the mean intercepts for the whole age class, the 24-40 age class had a strong relationship while the >40 age class had none however, when these age
classes were regressed against the mean intercepts at each phytomass collection point, there was no relationship for 24-40 age class, while >40 age class registered a strong relationship (Figs 3.8 & 3.9).

A regression between the mean sum of phytomass and mean sum of intercepts for each age class has a significant (p = 0.05) and very strong quadratic relationship $r^2 = 0.95$ showing phytomass increasing with number of intercepts until the >40 year age class where phytomass decreased as intercepts increased (Fig 3.10). A linear regression on these values also showed a strong relationship with $r^2 = 0.61$. 
Figure 3.7. Linear regression showing the relationship between sum of total fine phytomass and sum of total fine intercepts at corresponding point to phytomass collection for each age class.
Figure 3.8. Linear regression showing the relationship between mean fine phytomass and mean fine intercepts across the respective age class at each vertical 25cm interval. Numbers on the graph indicate the upper limit of the 25cm vertical interval associated with that value.
Figure 3.9. Linear regression showing the relationship between mean fine phytomass and mean intercepts calculated from those at corresponding points where phytomass was collected from in each age class.
Figure 3.10. Relationship between mean sum of total fine phytomass and intercepts, across age classes.

*Relationship between fuel quantity and complexity in sites*

A regression analysis between mean sum of fine phytomass and mean sum of fine intercepts for each site shows a modest significant relationship ($p = 0.013$, $r^2 = 0.39$) (Fig 3.11).

Figure 3.11. Relationship between mean sum of fine phytomass and fine intercepts for each site.
4 DISCUSSION

4.1 Assessment of surface and above ground fuel loading, type, and distribution

High fuel loading is known to correspond with more intense and severe fires (Van Wilgen, 1982; De Luis et al., 2004). While there are factors external to fuel such as fire weather that also affect intensity, fuel loading at a site is the most commonly used indicator for assessment of fire hazard (Plucinski, 2003). Fuel loads of between 0.8-1 kg m\(^{-2}\) are generally considered to be hazardous levels (Good, 1994; Plucinski, 2003). Average total fine fuel loads (standing phytomass and ground fuel) at all post fire ages assessed in this study exceeded the accepted hazardous level with loads ranging from 1.5 to 3.0 kg m\(^{-2}\). For a shrubland vegetation community these values may not be excessive since a study in South African fynbos found that aerial biomass alone, at 21 years since last fire, was 3.6 kg m\(^{-2}\) (Van Wilgen, 1982). Values up to 5.8 kg m\(^{-2}\) have also been recorded in Californian Chaparral (Schlesinger et al., 1980).

Total fine fuel does not necessarily reflect fuel that will combust in a fire. In this study total fine fuel incorporates live and dead fuel, which reflects potential fuel, or fuel that will only be fully consumed in the most extreme fire event (Chandler et al., 1983; Whelan, 1995; Catchpole, 2002). Available fuel is the term given to fuel that is expected to be consumed in certain known climatic conditions (Chandler et al., 1983; Whelan, 1995; Catchpole, 2002; Keith et al., 2002). The dead fuel array comprises the most significant portion of available fuel since it provides an ignition point, and can facilitate combustion of live fine fuels (Catchpole, 2002; Baeza et al., 2006). Fires usually initiate at ground level where most of the dead fuel is located. The radiated heat from fires burning at this level creates a drying effect on live fuel above, subsequently adding this fuel to overall
available fuel (Catchpole, 2002; Keeley et al., 2002; Keith et al., 2002). With the added effect of severe fire weather, the dead fuel array can comprise as little as 30% and foster intensive wildfires through the crown of shrublands, as a result of dead fuel being arranged beneath live fuel (Catchpole, 2002).

In shrublands assessed in this study, most dead fine fuel mass was located at 0-25cm from the ground in all age classes until the >40 year age class, where it was located from the ground to the crown. In comparison height and distribution of live fine fuel shifted with time since fire. For example in younger sites, from 7-18 years since last fire, height was around 1.50 m, and although all sites over this time had a similar height, the fire risk would probably be more pronounced between 14-18 years. This deduction was made because the dead-to-live fuel ratio is critical for determining the drying effect on live fuel (Keeley & Fotheringham, 2002). At 14-18 years since last fire, the proportion of dead fuel exceeded live fuel and the bulk of fuel mass was concentrated at 0-25cm from the ground, while at other sites live fine loading exceeded dead fine fuel loading. Dead fuel bulk and arrangement in the 14-18 year age class would therefore have more potential to convert live fuel into combustible material, while in the other age classes there would be insufficient energy generation from burning dead fuels to cause drying of live fuels. Additionally, in this 14-18 year age class, dead fuel was not confined to the 0-25cm interval, but was present up to 1 m. This would affect flame height since burning near ground level could facilitate flaming to move into the upper limits of the crown where the bulk of live fuel is located, and add to energy generation thus contributing to the drying effect on live fuel. The 24-40 and >40 year age classes also had similar arrangements of mass to the 14-18 age class, except that dead fine fuel extended to the upper height limit of the crown. This fuel arrangement would support fire at all levels in the vertical profile.
Increasing fuel accumulation is the product of fuel age, with fuel load increasing with time since last fire (Catchpole, 2002). Researchers have suggested that fuel does not always increase exponentially with age but will eventually reach an equilibrium (Catchpole, 2002). A study conducted in deep sand kwongan shrublands near Badgingarra, Western Australia, found fuel accumulation levelled at 7-17 years since last fire (Bell et al., 1984). Another study, conducted in heathlands stated that on productive sites fuel may continue to increase for up to 30 years since last fire (Catchpole, 2002). Fuel loading in shrublands was assessed in this study and shown to increase until 24-45 years since last fire. Fuel loads then decline at sites older than this. It is likely that fuel accumulation in shrublands reaches equilibrium at around 80 years since last burn. Sites presumed to be this age or older in this study showed little inter-site variability and little difference between each other in terms of live fine and dead fine fuel loading. An explanation for the decline in fuel loads that eventually even out in these older sites could be due to senescence (Bond & van Wilgen, 1996). Mediterranean shrubland systems are thought to senesce and standing dead vegetation is often a feature of long unburnt sites. This is attributed to the floristic composition of these communities, especially where reseeding non-sprouter species dominate and then die in long absence of fire (Bond & van Wilgen, 1996).

Plucinski (2006) suggested that pyric succession, with subsequent structural change, is responsible for the variable fuel accumulation patterns over time. The temporal floristic change in heathlands has been shown to support increased fire frequency with fuels accumulating rapidly in the post fire regeneration phase (Plucinski, 2006). Although the floristic composition at various post fire ages have not been studied in the sandplain shrublands used in this study, increases in fire frequency are a notable feature of this system. Fires often burn in areas that had only been burnt 6-10 years previously (Braun, 2006). However, the floristic composition of regeneration phases is not always consistent.
across the landscape, following a fire, because the nature of the fire itself can significantly influence recruitment success in the post-fire environment.

Fire intensity is known to affect the ability of vegetation to recover, subsequently affecting fuel loads after fire. Fuel load increases rapidly following fires in shrubland systems (Bond & van Wilgen, 1996; Pate & Beard, 1982; Keith et al., 2002; Morrison, 1996). Though many of the species that comprise these systems require fire for regeneration, and the intensity of a fire can significantly influence the composition of recruits (Bond & van Wilgen, 1996; Keith et al., 2002). Variability in fuel loads was observed between sites with post fire ages of less than 11 years in shrublands studied in this project. Sites in the larger fire scars would most likely been subject to intensive fires, since only extreme fires could burn such an expanse of the landscape. Sites of the same post fire age with variable fire history can also result in a different floristic composition, as the post fire response of the floristic community can feed into the nature of following fires. Explanations of variable fuel accumulation may also be due to factors external to the fire itself like soil changes and weather patterns. Unforeseen features such as the soil depth could be responsible for the structural changes in vegetation of sites with the same or similar post fire ages. Drought may also be responsible for mortality in the immediate post fire regeneration phase, while high rainfall events following fire may boost regeneration leading to rapid fuel accumulation (Bond and van Wilgen, 1996).

While overall ground litter is deemed insufficient to have an effect on shrubland fire behaviour (Keeley and Fotheringham, 2002), accumulation of ground litter mass was found to be significant across sites of various post-fire ages. Differences were between litter mass at recently burnt sites (from 7-11 years since last burn) and very long unburnt sites (24-80+ years since last burn). Despite sites within each age class having a highly variable litter mass, a trend emerged with litter mass increasing with post-fire stand age. In
the older sites (>40 post-fire age) above ground fuel loads declined but litter mass increased. This pattern is typical in senescing shrublands according to a study by Baeza (2006). It has been found in other studies that litter concentrates around the base of plants, and this discontinuous layer contributes little to fire spread (Bradstock, 1993). In this study litter continuity was not studied, however from field observations it was noticed that in older shrublands litter occurred in deep layers around the base of some plants, mainly Casuarinas.

Overall fuel load in the shrublands of the Transitional Rainfall Zone is highly variable in sites that have been recently burnt, and becomes more consistent as fuel age becomes older. Litter mass on the other hand shows a steady relationship where it gradually increases with fuel age.

4.2 Quantification of spatial continuity at local scales

The horizontal continuity of fuels on the surface or in the crown allows for lateral spread of fire through a landscape (Keith et al., 2002; Sugihara et al., 2006). Discontinuities, or spaces between fuel act as barriers to fire in most conditions and the size of these gaps is important for determining time at which an area can burn and how far reaching this fire will be, however there has been little research to identify thresholds (Christensen, 1985; Plucinski, 2003; Sugihara et al., 2006; Archibald et al., 2009). Where there is need to control fire spread, management often deploy measures such as fuel breaks to create discontinuities (Sugihara et al., 2006). Not all fires can be limited by discontinuities though, because fire may still travel through patchy landscapes as a result of weather conditions. In younger shrublands the continuity of patches is generally low which increases the probability that fires will burn out in moderate weather conditions (Keeley &
Fotheringham, 2006). When fire weather is severe, often in the case of high wind and dry days, the limitations of interpatch space can be overcome and the fire can readily spread throughout the landscape (McCaw et al., 2003; Keeley & Fotheringham, 2006).

Severe fire weather has been known to facilitate fire spread in shrublands less than two years old (Catchpole, 2002; Keith et al., 2002; Plucinski, 2003). Mean patch size in the shrublands in this study increased as time since last fire increased, though the distance separating the patches, or mean inter-patch space did not get smaller in comparison, but was varied between age classes. A study in South Australian heathlands found interpatch space to have about 30% coverage at 10 years after fire, and remained constant at 15 years after fire (A. M. Gill et al., 1981). This was not the case in these shrublands, interpatch space was still variable after 10 years and seemed to be governed by events such as senescence, most notably interpatch space decreased significantly between 24-45 years, and large interpatch spaces returned at >45 years since last fire. Patch continuity is also a determinant of fire frequency under moderate weather conditions, the typical age at which fire can be carried through kwongan shrublands is 8-15 years (Abbott, 2003). In the Joseph Land System, fires have reportedly occurred on areas that were burned 6-10 years previously (Braun, n.d.). This fire would most likely have burned in moderate weather conditions, and based on patch continuity and fuel loading in this study fire could burn at sites from 14 years after fire. Under severe weather, fires may burn at sites with post fire age of 3 years due to rapid fuel accumulation in the immediate post-fire period.

Continuity of fuel within patches and the size of these patches contributes also to the extent of fire as it can allow for more intensive fires which spread rapidly (Perry, 1994; Whelan, 1995). Differences in percentage patch cover in shrublands studied were mainly between the older and younger patches, with older sites having greater percentage patch cover than the younger sites. A study conducted in kwongan shrublands found maximum percentage
patch cover was 75%, similarly in heath vegetation in South Australia 70% patch cover was recorded, while 55% was recorded in Californian chaparral 70 years after fire (Bell et al., 1984). Maximum percentage patch recorded in this study was slightly higher than those recorded in the other systems at 84% coverage by 24-40 years since last fire. While the long unburnt age classes, 24-40 and >40 years, both had large patch size, interpatch space showed large differences. The 24-40 year age class had minimal average interpatch space at 0.38 m making patches almost continuous, while the interpatch size in the >40 year age class was quite large with an average of 0.72 m. There were also significant differences in patch variability between age classes, with variability increasing as sites got older. In the >40 year age class shrubs were beginning to senesce which resulted in the large interpatch spaces and site variability observed in this study. In younger age classes patches were of a similar size and were spatially consistent. In heathlands this is thought to be quite unusual, as uniform continuous fuel is not often seen (Keith et al., 2002). Other shrublands are noted for fuel changing from continuous to discontinuous over small areas (Catchpole, 2002). Another study found that in this young phase vegetation is uniform and any variation is a result of “underlying topographic and geological variation” rather than succession (Huston, 2003). As shrublands in this study became older the patch size and continuity did start to show variability, especially in sites 24-29 and 60-80 years since last fire, which had much larger patch sizes compared to other sites in the same age class. There is the possibility that differences in patches between these sites and others in the age class can be attributed to temporal differences, as sites in these age classes are 8 or more years apart from each other, with some showing evidence of senescence.

In shrublands, litter at the ground level has little importance in the spread of fires, therefore fuel in the upper layers of the profile determine the extent of any fire (Sugihara et al., 2006; Keeley & Zedler, 2009). Fires that persist in the upper levels of the profile are
termed crown fires (Sugihara et al., 2006). There are three stages of a crown fire; passive, active, and independent (van Wagner, 1977). Passive occurs where trees are torched from fire burning at the surface: this occurs when fuels are sufficient to ignite the crown, but there is not enough wind to generate fire spread throughout the crown (Chandler et al., 1983). Active fires are characterized by fire spreading when burning at the ground level and crown simultaneously creating a wall of fire, these fires are intensive and to be sustained require high winds, low crown base heights and high crown bulk density (Sugihara et al., 2006). Independent crown fires occur when fires are confined to the crown only and burn ahead of the surface fire, this type of fire require very windy conditions and are often short lived (Sugihara et al., 2006). A study on crown fire development in shrublands found crown base height, fuel density, and weather conditions were the most important in determining the type of crown fire (Plucinski, 2003). Without wind, sufficient density of aerial fuels, and continuity of dead fuels in the crown is enough to facilitate independent crown fires (Plucinski, 2003). Also where there is enough fuel to support surface fires then there is greater support for crown fires (Plucinski, 2003). In this study at younger sites density and patch continuity is low, and the proportion of dead fuel is less than live fuel, thus ignition and spread would likely not be supported. In older sites the proportion of dead fuel exceeds live fuel near the surface, and there is dead fuel present throughout the vertical profile. These older sites are also spatially continuous and dense, which would support lateral spread of fire throughout the crown. Continuity of crown fuels is prevalent in shrublands, especially in senescent vegetation phases where there is a significant amount of dead fuel retained in the crown as well as accumulation of dead fuel at the surface, these conditions drive the intense and severe fires that are frequent in these systems (Baeza et al., 2005).
In comparison to the small amount of literature on spatial continuity in shrublands systems, the system that was studied seemed to have slightly higher patch size, though senescence was an overriding feature determining interpatch space. Assessment of crown continuity was in line with structural characteristics prevalent in other shrublands, with younger sites lacking fuel to support wild fires in moderate conditions, while older sites satisfied the criteria for intensive fires.

4.3 Assessment of density and arrangement of fuel types in the vertical profile

Fuel density and its vertical arrangement has implications for fire behaviour in shrubland systems by contributing to fire intensity and spread (Wilson, 1993). As fuel density decreases, porosity increases which enhances fuel/air mixing, causing greater convective and radiative heat transfer, and more intensive fire (Keeley & Fotheringham, 2002; Plucinski, 2003; Baeza et al., 2005). Depending on the type of fuel present and environmental conditions (e.g. weather) decreasing density has a threshold at which there is insufficient heat to ignite unburned fuel particles (Plucinski, 2003). Shrublands in this study that were burnt fairly recently (7-11 years since last fire) showed fuel bulk increases from the ground to the crown, with the live fine and dead fine fuel being the most dense at 0-25cm from the ground. As time since fire increases, the density of live fine fuel becomes more consistent throughout the profile, while the dead fine fuel maintains bulk distribution at the ground level that gradually increases as height above the ground increases. In these younger sites, the dead fine fuel was comparatively lower than the live fine fuel, which is a common feature of juvenile heathlands, where fire risk is considered to be small (Baeza et al., 2002). Sites that are >40 years since last burn, begin to show more erratic vertical distribution of fuel which seems to lack definite structure. Non stratification of fuels in the
vertical profile is often observed in shrublands (Plucinski, 2003; Cruz et al., 2008). Amongst the lack of structure in the vertical profile, the location of the crown base height is significant for the development of crown fires that occur in these systems, as it facilitates propagation of fire into the crown (Moritz, 2003; Plucinski, 2003). When the crown base is close to the surface fuels or is in direct contact with surface fuels, as often is the case in shrublands, then the crown becomes more ignitable (Plucinski, 2003). Though if there are significant gaps then greater fire intensities and flame heights are needed to bridge the gap (Plucinski, 2003). In the shrubland system in this study, the crown base was close to the ground and ladder fuels comprising twigs and branches connected surface fuels to the crown.

In the long unburnt sites, dead fuel was present at all levels in the profile. This distribution of dead fuel in the older sites has been noted to be particularly common in heathlands where shrubs senesce (Plucinski, 2003). As these shrubs die they retain their dead branches but also have significant space surrounding the aerial fuel which enhances their flammability, and has significant implications for the development and intensity of crown fires (Wilson, 1993; Keeley & Fotheringham, 2002; Schwilk, 2003). In heathlands this has been known to occur on a large scale when certain species become senescent (Plucinski, 2003).

Vertical fuel density and type of shrublands in this study were found to be consistent with similar systems, with the live fine fuel overriding dead fine fuel at juvenile stages, and the older sites have more complex array. The fuel complexity and presence of dead fine fuel in these older sites provides the means for very intensive wildfires, especially on severe fire weather days.
4.4 Exploration of relationships between density and quantity measures

Destructive sampling of above ground biomass is the most common and accurate method to assess fuel loading, especially in shrublands. However, his method can be time consuming, difficult, and the quantities of vegetation that need to be removed are undesirable (Plucinski, 2003). In addition this sampling technique does not allow for quantification of fuel at various levels to assess where fuel mass is concentrated. One objective of this study was an attempt to reduce the need to destructively sample by exploring relationships between phytomass and density measures. There are other non-destructive methods that use this regression analysis technique, some of these include relating stem diameter, number of stems, cover and height to phytomass though again none of these allow for quantification at various levels and most have low accuracy (Catchpole & Wheeler, 1992; Plucinski, 2003; Baeza et al., 2006). The methods in this study used a cube to sample small amounts of phytomass at every 25cm vertical interval and related these values to the number of recorded intercepts of a pole at each height. Results from this approach show promise, with some relationships between the two parameters being particularly strong such as the strong correlation between raw values of measures of phytomass and density at specific sites. This relationship did hold when all sites were included in the regression. With further testing this method has the potential to be used in estimations of fuel loading at a site, and is versatile as it can provide more detail on density and mass at vertical intervals.
4.5 Conclusion

In conclusion, this shrubland system was found to be heterogeneous with variability that was present at small spatial scales, which is characteristic of similar systems in Australia and throughout the world. While the juvenile shrublands has some aspects that were consistent throughout such as density measures and patch/interpatch characteristics, there was no trend for any parameter observed where fuel characteristics increase with age or eventually plateau. In this respect fuel characteristics were highly variable with age, which is possibly due to underlying site features such as soil depth and climate. The timing of rainfall after a fire can be critical in boosting recruitment, as is the nature of the soil. Underlying soil differences such as shallow concrete layers could be responsible for the slow growth rates at some sites. In addition, pyric succession, or the composition of dominants after a fire could be influenced by the fire itself. Different successional phases where species are short lived, or die out as time without fire increases could also be responsible for variability of sites. Senescence was found to be a prominent feature in long unburnt sites, and was observed to alter fuel characteristics significantly. Post fire age alone should not be used as the only factor to compare fuel characteristics. Other features, mainly environmental features such as underlying soil conditions and climatic conditions at the time of the fire and following the fire need to be taken into account for this type of assessment as they have been suggested from other studies to be important in determining the overall fuel dynamics of system. This study highlighted the nature of fuel dynamics that currently exist in this system and for managers this information has shed light on the nature of fires to be expected at these post fire ages.


6 APPENDICES
6.1 Appendix I

Figure displays the mean number of live fine intercepts for each vertical interval across all replicates.
Figure displays the mean annual rainfall at properties surrounding Charles Darwin Reserve in the Transitional Rainfall Zone.