EMERGENT PATTERNS IN THE MOSAIC OF PATCH BURNING VARY WITH THE FIRE ENVIRONMENT AND LANDSCAPE CONTEXT IN SOUTH-WESTERN AUSTRALIA

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Abstract
Patch-burning to create a fine-grained mosaic of vegetation at different post-fire stages is one management strategy to maintain habitat heterogeneity across space and time. However, the landscape and fire environment context, the ecologically appropriate range of fire regime diversity, and the operational guidelines for implementation all remain poorly understood. Here we provide the landscape and fire environment context for a patch burning mosaic in four types of landscape in south-western Australia. We also introduce a technique for mapping burn severity classes and intersecting these with vegetation complexes to quantify which components of the landscape burn, and with what severity under a range of burning conditions. We aim to analyse and compare the emergent burn patchiness under a variety of seasonal and weather conditions; and expect high intensity fires burning under dry conditions to reduce mosaic patchiness in comparison with low to moderate intensity fires burning under moist conditions. However, we also expect greater vegetation heterogeneity to lead to greater variability in burn patchiness. We believe that there is potential to implement fine-scale fire mosaics by patch burning, and to use this approach to better predict fire patchiness and scale in a variety of landscapes under a range of conditions.

Keywords
Land classification, Landscape Conservation Units, Vegetation Complexes, Change detection methods.

Introduction

There is an intimate association between abiotic and biotic diversity so that landscapes composed of spatially heterogeneous abiotic conditions provide a greater diversity of potential niches than do homogenous landscapes (Burnett *et al*. 1998; Nichols *et al.* 1998). Subdued topographic relief is a conspicuous feature of the temperate high rainfall zone of south-western Australia (Wardell-Johnson and Horwitz 1996; 2000). However, this area is notable for exceptional fine-scale abiotic richness, high levels of floristic diversity and relictual taxa (Wardell-Johnson and Horwitz 1996; 2000), and displays complex ecological interactions (e.g. Garkaklis *et al.* 2003). These factors highlight a need for increasingly sophisticated conservation management (Hopper and Gioia 2004), though there is continued debate as to the appropriate scale and diversity of management regimes for biodiversity conservation (Wardell-Johnson and Horwitz 1996; 2000; Abbott and Burrows 1999; Burrows and Wardell-Johnson 2003).

The fire-habitat mosaic concept has become an important, though controversial paradigm in environmental management (e.g. Keeley and Fotheringham 2001; Gill *et al.* 2003; Bradstock *et al.* 2005). There is increasing evidence that a diverse fire regime benefits biodiversity in fire-prone environments leading to recommendations to increase variability in fire management. Much of this stems from growing evidence that: (i) there is no one fire regime that is optimal for all organisms (e.g., Bradstock *et al.* 2002; Abbott and Burrows 2003) leading to the conclusion that a diverse regime at appropriate scales is optimal for biodiversity conservation at the landscape scale, and (ii) that heterogeneity of fire regime is an important driver of habitat structural complexity, with demonstrated implications for biodiversity (e.g., Russell-Smith *et al*. 2002; Price *et al.* 2005). Patch-burning to create a fine-grained mosaic of patches of vegetation at different post-fire (seral) stages has been suggested as a management strategy for creating habitat heterogeneity across space and time in forested ecosystems of south-western Australia (Burrows and Wardell-Johnson 2003; Burrows *et al.* 2003). However, three key areas remain poorly understood; the landscape and fire environment context for the patch burning mosaic, the ecologically appropriate range of fire regime diversity, and the operational guidelines for its implementation.

In Western Australia, the Department of Conservation and Land Management (CALM) has overall responsibility for the management of public lands and for the conservation of the states's biota. CALM has proposed implementation of a pilot fire mosaic project which uses the planned and frequent introduction of fire into the landscape to create a fine-grained mosaic of interlocking patches of vegetation at different stages of post-fire development (Burrows *et al.* 2003). Although management assuming a fine-scale mosaic has been advocated (Wardell-Johnson and Horwitz 2000), the

efficacy of this approach for the biota has yet to be quantitatively assessed. The reality and stability of vegetation boundaries under different regimes of disturbance is also yet to be determined in south-western Australia.

In this paper we examine the landscape and fire environment context for a patch burning mosaic by introducing the hierarchical approach to land classification developed by Mattiske and Havel (1998; 2002) for conservation planning in south-western Australia. We also introduce a technique for mapping burn severity classes and intersecting these with vegetation complexes to quantify which components of the landscape burn, and with what severity under a range of burning conditions. We aim to analyse and compare the emergent burn patchiness in four contrasting landscapes in south-western Australia, burnt under a variety of seasonal and weather conditions. This approach is based on the assumption that intrinsic variability of the vegetation mosaic and seasonal variation in the dryness of the landscape associated with a Mediterranean-type climate, will determine the resultant fire mosaic.

Methods

Delineation of heterogeneity in Landscape Conservation units in south-western Australia and choice of study sites

Land classification approaches enable land use decisions to be made in a systematic and informed manner (Havel 1981). In the absence of adequate data on the distribution and abundance of species in a region, land classification approaches are used to delineate discrete units of the landscape (Pressey 1994; Ferrier 2002). These classifications seek to map the landscape into a series of units with greater heterogeneity between than within units (Ferrier 2002). A hierarchical system has been developed in the forested south-west region of Western Australia to account for the different scales required for different conservation planning purposes.

The pattern of vegetation in the south-west forested region reflects the underlying landform and soils patterns, but is reflected poorly by the overstorey species, making aerial photographs of limited use in regional vegetation mapping (Wardell-Johnson and Horwitz 1996). Mattiske and Havel (1998) provided and mapped (at 1: 250 000 scale) a set of 315 Vegetation Complexes (plus one mapping unit that included lakes and open water) for the south-west forested region of Western Australia, essentially corresponding to all possible combinations of geomorphology, landforms, soils (e.g. Churchward *et al.* 1988; Tille 1996) and climate (Gentilli 1989). Havel and Mattiske (1998) agglomerated the Vegetation Complexes to provide a reduction in the number of map categories to 119 Ecological Vegetation Systems, mapped at the scale of 1: 500 000 to provide an overview of the whole region. The agglomeration utilized similarities in vegetation and the underlying environmental factors.

A further reduction through agglomeration of the Vegetation Complexes into 29 Landscape Conservation Units (LCU) was carried out by Mattiske and Havel (2002) to provide more manageable mapping units. The chosen strategy was directed towards providing compactness of map units; the criteria for agglomeration being inclusion, contiguity and proximity so that ecologically dissimilar systems were combined but which repeatedly occur together in a particular climatic zone, The resulting LCUs resemble the land systems of Christian and Stewart (1953), and reflect recurrent patterns of landforms and vegetation. The maps of Landscape Conservation Units were mapped at both the scale of Vegetation Complexes (1:250 000) and the Vegetation Systems (1: 500 000); to be used in activities associated with the management of broad scale landscape processes such as fire and pathogens.

This study uses four of the LCUs developed by Mattiske and Havel (2002), including the study region (Southern Hilly Terrain LCU) of the current fire mosaic burning trials (Burrows *et al*. 2003), for assessing variation in cover change in the vegetation complexes developed by Mattiske and Havel (1998). This approach enables us to ask whether there is proportionally more change between units in areas of more heterogeneous landscape features (i.e. Southern Hilly Terrain and Southern Swampy Plain) than in areas with less heterogeneous landscape features (Blackwood Plateau and Central Jarrah). The rational for choosing the various LCUs was also based on each being relatively large in area so as to include sufficient fires over the period of the study (2001-2005), and within the high rainfall zone of the south-west.

The study LCUs

Each of the LCUs occur in the per-humid to hyper- humid area, with the Blackwood Plateau and Central Jarrah LCU' s notable for their gently undulating topography, while the two south coastal LCUs (Southern Swampy Plain and Southern Hilly Terrain) are notable for their variation in landforms, soils and vegetation types (Figure 1).

The Southern Hilly Terrain LCU is an archipelago of high hills (up to 360 m asl) extending from the southern edge of the Darling Plateau toward the southern Ocean, surrounded by, and enclosing swampy and sedimentary plains. It

includes valleys of major streams cutting through the hilly terrain (Mattiske and Havel 2002). The unit extends east and north from Walpole towards Denmark and Lake Muir, over a considerable climatic range from hyper-humid to humid. The annual rainfall ranges from > 1400 mm in the south-west to 900 mm in the north-east. The corresponding range in the summer evaporation is much narrower (from 400 to 450 mm). The vegetation of the unit is unique with many endemic species.

The Southern Swampy Plains LCU is also relatively heterogeneous and extends along the southern coast from the mouth of the Warren River to the mouth of the Frankland River. It is the lowest portion of the Ravensthorpe Ramp, and consequently is poorly drained. It includes uplands rising above swampy plains and valleys incised into the swampy plains. The unit occurs within the per-humid to hyper-humid climatic zone (annual rainfall 1100 mm – 1400 mm, summer evaporation < 500 mm - Mattiske and Havel 2002)).

The Blackwood Plateau LCU stretches from the Margaret Plateau in the west to the Darling Plateau in the east, and from the Abba Coastal Plain in the north to the Blackwood-Scott Coastal Plain in the south. Apart from the northern escarpment and northern tip there is an overall gentle slope southward. There is parallel deterioration in drainage except for the river dissection. This unit is humid to per humid climate with annual rainfall ranging from 1300 mm to 900 mm, and summer evaporation from 400 to 550 mm (Mattiske and Havel 2002).

The Central Jarrah LCU extends along the western margin of the Darling Plateau between Serpentine and the Preston Rivers in the humid climatic zone (annual rainfall 900 – 1300 mm, summer evaporation 550-700 mm). The southern third of this unit is per humid (annual rainfall > 1100 mm, summer evaporation < 550 mm). This unit includes mildly undulating plateau uplands with shallow valleys and moderately to deeply incised valleys with slopes largely stripped of laterite and the Darling Scarp (Mattiske and Havel 2002).

To investigate the importance of seasonal variation in landscape dryness as a factor regulating the patchiness of fire, we will analyse the patchiness of all large scale (> 300 ha) operational prescribed burns and wildfires that occurred in the four LCUs between 2001 and 2005 (as shown in Figure 1). We will also include data on the seasonality, Fire Danger Index and other information about each fire that can be used to interpret the derived patterns . We hypothesise that fire patchiness is increased in landscapes that contain inherently high heterogeneity of vegetation associations, and when strong moisture differentials exist across the landscape. This will necessitate the development of novel landscape mosaic metrics to quantify patchiness and the fire-induced mosaic in a biologically meaningful way. Fundamental to measuring and understanding fire-induced habitat mosaics at landscape scales is an ability to reliably and efficiently map burnt patches through space and time.

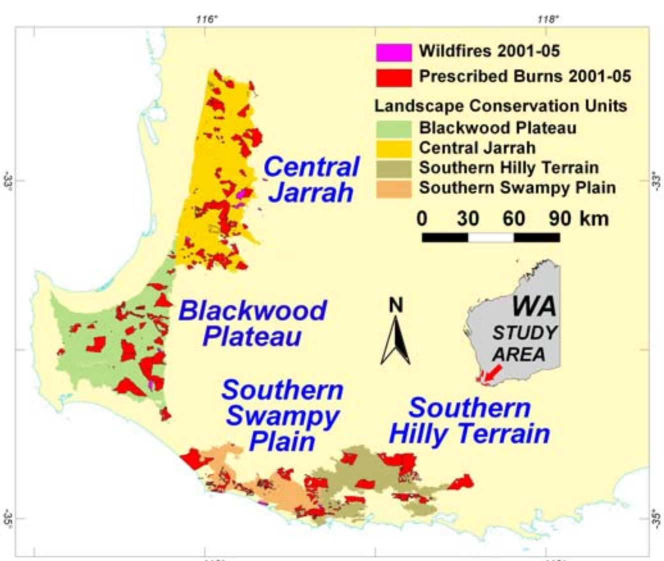

Figure 1. The south-west of Western Australia showing the four Land Conservation Units (LCUs) used as study areas, and all fires within these areas between 2001 and 2005, the data for comparisons between vegetation complexes, and between Landscape Conservation Units.

Table 1. The number of fires larger than 300 ha in the four study LCUs between 2001 and 2005.

	No of Planned Burns	No of Wild Fires
Central Jarrah	47	3
Blackwood Plateau	33	2
Southern Swampy Plain	26	2
Southern Hilly Terrain	18	2

Choice and development of Image enhancement and change detection methods

In image processing, there are various methods to enhance a class of features, such as fire signatures. These methods are based on applying simple mathematical operations and statistical analysis to the satellite-based data. A simple mathematical operation can be applied to selected spectral bands – substraction, multiplication, ratio, etc., such as Normalised Difference Vegetation Index (NDVI), Normalised Difference Fire Index (NDFI), Fire Effect and so on. The other approach is to analyse all bands of the data and use statistics to discriminate information recorded in all bands of satellite-based imagery, such as Multi-temporal Data Averaging, Median Analysis, Principal Component Analysis (PCA) and Canonical Variate Analysis (CVA). It is also possible to select training areas on the imagery, run a statistic package using these training areas and make a relative contrast. This method is more complicated and although the resultant images are better than those from mathematical operations or whole dataset statistics, this method does require intensive user interaction with the process.

The Normalized Difference Vegetation Index (NDVI) (Rouse *et al.* 1973), which resulted from the division of values in one band by the corresponding values in another (Lillesand and Kiefer 1987), has the best sensitivity to changes in vegetation cover and moderate sensitivity to the soil background and the atmosphere, except at low plant cover. As an algorithm, the Vegetation Index is used to reduce multiple bands of data to a single number per pixel that predicts canopy characteristics (Jensen 1996). Most vegetation indices are based on significant differences in the shape of spectral curves associated with chlorophyll-dominated green vegetation, senescent vegetation and dry bare soil.

The NDVI is commonly applied to fire-mapping (Garia-Haro *et. al*. 2001; Sunar and Özkan 2001). Salvador *et al.* (2000) used NDVI to a sequence of Landsat MSS imagery to use in a semi-automatic method for detecting burnt areas. The NDVI is, however, not as effective in areas of sparse vegetation and in areas where there has been significant recovery of the vegetation after a fire event. As it computes the normalised difference of brightness values for monitoring vegetation, the NDVI cannot distinguish between burn areas and rock outcrops or exposed soil. Variation in greenness within the context of the whole region also significantly discounts the applicability of NDVI to fire-mapping for a large area. Koutsias and Karteris (2000) examined the discriminator ability of the Landsat TM bands between fire and other land cover types. They found that Bands 4 and 7 provided the best discrimination between crops and fire signatures and Band 5 and 7 provided the best discrimination between forest and fire signatures.

Through the Pilbara fire-mapping project, Li *et al.* (2001) adopted the Normalised Difference Fire Index (NDFI; Equation 1), a variation of NDVI using Bands 4 and 7 instead of Bands 4 and 3. They found that this variation performed better than NDVI in identifying burn areas in a single image.

$$\text{NDFI} = \frac{TM\ band\ 4 - TM\ band\ 7}{TM\ band\ 4 + TM\ band\ 7} \qquad (1)$$

The NDFI on its own is an efficient algorithm for enhancement of fire signatures in grasslands but it is in most cases inadequate for the forest region of south-western Australia. This is because fires may not cause significant changes in greenness on one hand, whereas dieback and logging can result in soil exposure or substrate removal on the other hand. Hence an approach using Principal Component Analysis (PCA) and the Canonical Variate Fire Index (CVFI) was developed. This involves the statistical analysis of bands 1-5 and band 7 from the combination of the post fire scene and up to three pre-fire scenes.

Both pre-fire and post-fire NDFI, CVFI or PCA were needed for image differencing, which detected the actual vegetation changes in greenness caused by fires, and eliminated the effects of geology, dieback, and seasonal fluctuation in greenness of vegetation. The resultant image, showing vegetation changes in response to fires, was used for unsupervised classification and generation of burn boundaries.

Using ERMapper, polylines were generated from the result of image differencing. The vector data of burnt areas was translated into ESRI Arc/Info. Polygon attribution, the final step in producing a vector fire map, was made possible by developing a model for attributing burnt/unburnt areas. It is common that prescribed burns and wildfires, when burning through a heterogeneous area, may leave patches of unburnt vegetation. Conversely, wind may start small spot fires inside unburnt areas to create small fire scars in the unburnt patches. The fire map has been produced automatically by

a map attribution subroutine. The fire map in vector format is also attributed to start_to_end dates using NOAA AVHRR and MODIS hotspot data.

The fire maps produced from satellite images were followed by field-checks to investigate the accuracy of image interpretation and fire boundary generation. This involved visits to a wide range of sites across the region to check the accuracy of the information and to check any anomalies detected. CALM's staff and regional fire officers provided ground-truthing wherever access was possible. During field validation, burnt area and unburnt pockets inside larger burnt areas were checked against the enhanced images and the fire maps derived from these images. The categories of fire effects (burn severity classess) determined from satellite images were compared to the categories of burns identified in the field.

Landscape variation and fine-tuning of mapping process

Technically, it is not possible to apply one overall algorithm to the whole region of the south-western forests because of the considerable variation in landscape and vegetation. However, it is achievable to develop one universal process that accommodates the differences both in Landscape and vegetation if the region is subdivided to a number of sub-regions based on the types of landscape and associated vegetations (i.e. LCUs and Vegetation Complexes). This issue was dealt with by various subroutines specifically prepared the south-western forest region of WA. For instance, an algorithm specifically developed for the northern Jarrah forest may be very different to that applied to the southern Karri forest. However, the effects of landscape and vegetation can be minimised by developing specific routines embedded in the overall processing. It takes time initially to do this but once developed, fire-mapping by batch processing will be possible over many years.

Prescribed burn assessment

Immediately following a fire event, it is important to assess the location, amount and degree of the fire effect (the burn severity). This is currently undertaken in CALM using information recorded from field operations and Landsat TM or ETM.

Satellite imagery is acquired twice a year over the south-west forest region during spring/summer and autumn/winter and processed to identify burnt areas. This is not a simple exercise since satellite imagery is sensitive enough to detect change but not to identify the cause of the change. CALM has developed procedures to improve the reliability of mapping areas that have been affected by fire. This has been achieved by using image-processing techniques developed by CALM Fire management Services (Shu *et al*. 2001) that are validated using CALM's Fire Reporting Systems, which record wildfire reports and prescribed burn activities on CALM-managed lands. We then assessed the area of vegetation change within each of the five categories depicted in Figure 1. We calculated the area of each change variable (no change, up to 25% change, 25-50 % change, 50-75 % change and > 75 % change), immediately before a fire and soon after a fire, so that the difference can be attributed to the fire. We will be using multivariate approaches using the numerical taxonomic package PATN to examine structure and pattern, in the resultant data matrix of cover change and vegetation complex. Comparisons between LCUs will then be undertaken using Chi Squared and other analytical approaches.

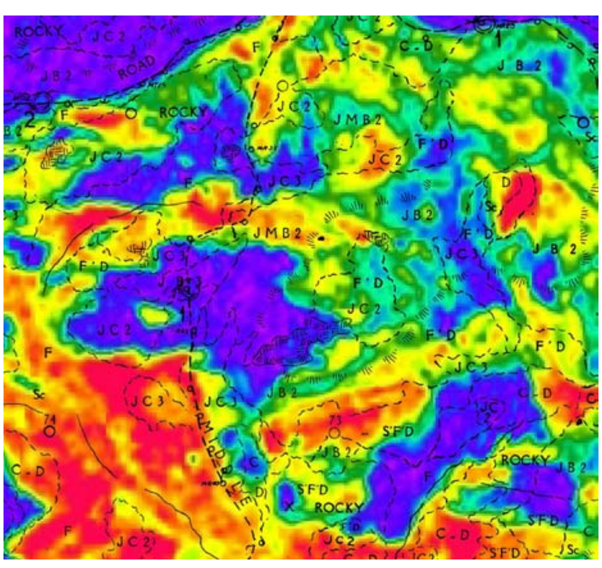

Figure 2. Post_burn assessment of change in vegetation cover based on Landsat TM data. Pink and dark blue areas are classified unburnt; Light blue indicates up to 25%, green 50%, yellow 75% and red 100% of biomass change after the fire. Labels show forest types.

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