Fire in arid and semi-arid Australia

1998 – 2004

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Thesis submitted for the degree of

Doctor of Philosophy

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August 2009

Chapter 1

INTRODUCTION

1.1 Introduction

Arid and semi arid Australia comprises 70% of the continent. Fire in these areas is characterised by pulses of large intense wildfires following above average rainfall in preceding years. These pulses can range between a few years to over 20 years apart (Allan and Southgate, 2002; Edwards et al., 2008).

In the Northern Territory's arid zone, above-average rainfall from 1999 to 2002 resulted in high fuel continuity, which led to fires burning more than 500,000 square kilometres (70% of the area) between 2000 and 2002. Similar widespread fires also occurred in arid and semi-arid Western Australia, and to a lesser extent in the pastoral zone of South Australia (Ellis et al., 2004). Fires threatened homesteads, sacred and cultural sites, damaged infrastructure, destroyed pasture and fences, killed cattle and other animals, and posed health risks to the public They also killed mature mulga plants, increasing the opportunity for spinifex to invade these fire sensitive communities, and homogenised the fire age over very large areas (Allan and Tschirner, 2009; Edwards et al., 2008).

The previous period of widespread fires throughout central Australia was between 1974 and 1977, when a comparable area was burnt (Edwards et al., 2008; Griffin et al., 1983). There have been other large fires in arid Australia in the recent past, also associated with periods of above average rainfall. Fires west of Alice Springs in 1983 and 1985 burnt over 25,000 square kilometers. Between 1989 and 1991 over 7,000 square kilometres (including part of Uluru – Kata Tjuta National Park) were burnt, while during 1994 a series of wildfires burned over 100,000 square kilometres of the Tanami and Great Sandy Desert (Allan and Southgate, 2002).

These wildfires highlight the need for better links between the development of spatial fire history databases and the implementation of land management actions (Allan and Southgate, 2002). While events such as these reinforce the general publics' view of fire as an element of destruction, this is only one side of the story. People affected by fires in arid and semi-arid Australia all have different outlooks and priorities about fire and its use.

Fire has been a crucial element in shaping our world for millions of years, whether caused naturally by lightning, or by humans, either accidentally or on purpose (Bird et al., 2003; Curtin and Western, 2008; Kershaw et al., 2002; Levine et al., 1999; Tinner et al., 2005; Wierzchowski et al., 2002). With the advent of satellite imagery we can appreciate for the first time just how widespread it is over the globe (Dwyer et al., 2000; Tansey et al., 2008), occurring in almost every environment from tropical rainforests (Aragao et al., 2008; Langner et al., 2007) to deserts (Allan and Southgate, 2002; Brooks and Matchett, 2006; Ravi et al., 2007). A fire history or regime describes how repeated fires disturb a particular site, and includes measurements of fire distribution, frequency, intensity, extent, season of occurrence and type of fire (Brooks et al., 2004; Gill, 1975). Different fire regimes can have profound impacts, either positive or negative, on our natural environment, society and its economics, and the world's climate (Levine et al., 1999).

Fire can be managed through suppression of wildfires, or by prescribed burns for land management, fuel hazard reduction or ecosystem restoration. Management of fires has varied over the centuries but we now realise that we must attempt to balance all the elements. While using fire to our advantage and preventing it from causing damage to our property or ourselves, we must also strive to maintain the balance of our ecosystems and climate (Dombeck et al., 2004; Levine et al., 1999). In theory, current legislation in Australia tries to take all aspects into account, but in reality, due to the lack of objective knowledge of the complicated relationships between fire regime and its drivers, there are few explicit regulations or guidelines for defining and controlling fire regimes (CSIRO, 2001a).

It is vital that land managers have the ability to plan for fires, whether caused by natural or human ignition, and are ready to manage their impact in an effort to enhance their positive aspects and minimize the negative. Management must be implemented based on the best information available. An understanding of current (and if possible, past) fire regimes is critical in this process.

Little knowledge of past regimes in arid and semi-arid Australia has been gained from prehistoric charcoal records or accounts of the explorers from the 18th and 19th centuries (Bowman, 1998; Burrows et al., 2004; Fensham, 1997; Gill, 2000; Kimber, 1983). Until recently the majority of arid and semi-arid Australia has had no mapped fire history. The advances in remote sensing and GIS (Geographic Information System) technologies are making this easier, with their capability to improve detection, monitoring, mapping, modeling and forecasting of fire events. While much work has been carried out in the forests of the world, the arid and semi-arid environments, which cover one third of the world's land surface and over two-thirds of Australia, have been largely ignored by comparison. Early aerial photography, and Landsat satellite images from the mid 1970's to the present, have been used to provide information on fire frequency, extent, and seasonality in some arid and semi-arid areas of Australia to create spatial databases, but these have been of limited spatial and/or temporal extent (Allan and Southgate, 2002; Burrows et al., 1991; Curry, 1996; Edwards et al., 2008; Haydon et al., 2000; Kaethner, 2004). While all these research projects are very valuable in their own right, their results cannot be directly compared, as they all used different methods of data collection and analysis. They have only had a regional focus and have not been able to provide a continental perspective on the spatial and temporal patterns of fires.

Recently, Satellite Remote Sensing Services at Landgate (the Western Australian Land Information Authority; formerly known as the Western Australian Department of Land Information (DLI), and before that, the Department of Land Administration (DOLA)) have compiled fire history datasets from the relatively coarse (1.1 km resolution) NOAA-AVHRR satellite imagery. These are now available for the Kimberly region back to 1993, the whole of WA back to 1995 and the whole of

Australia back to 1998 (Allan, 2003). They have mapped both active fires (fire hotspots - FHS) at a 1 square kilometer resolution, and fire scars (fire affected areas - FAA) at a 4 square kilometer resolution (Craig et al., 2002).

While not as detailed or accurate as Landsat imagery, the availability of this NOAA-AVHRR data can now provide a valuable and cost-effective insight into the broad regional fire patterns across Australia. This data has been used in a number of studies (Craig et al., 2002; Edwards et al., 2008; Russell-Smith et al., 2003e), but a thorough analysis of the seven years of data has not been conducted for the entire arid and semi-arid regions of the country. Neither has the accuracy of the datasets been assessed in these regions. This data has not been linked to other factors (such as lightning, climate and weather, vegetation, soil type or management strategies) that may influence the fire regime in these dry climate zones, to analyse possible relationships with a view to building predictive models.

Current fire forecasting tools available for arid and semi-arid conditions in Australia are generally limited to short-term local predictions. They relate to the chances of a fire starting, its forward rate of spread, intensity and difficulty of suppression in either grasslands (Allan and Southgate, 2002; Cheney et al., 1998; McArthur, 1966), or spinifex (Allan and Southgate, 2002; Burrows et al., 2006c). Short-term predictions like these are most useful as a decision support mechanism for planning management fires, or the allocation of resources for fire fighting by operational fire fighting centers, of which there are very few in arid and semi-arid Australia. Here, if a large fire develops, it is often next to impossible to contain it, due to lack of manpower, equipment and accessibility in remote areas (Edwards et al., 2008).

As periods of large intense wildfire are relatively infrequent in these environments, it is difficult for individuals to develop skills to manage them, and there is little incentive to develop explicit fire management strategies. Little has been done in the way of Decision Support Systems or longer term predictive modelling for these areas. Mid to long term management decisions are often based on practical experience and local knowledge, but with the high turnover of management staff in these remote areas it is difficult to build up expert knowledge (Edwards et al., 2008). Something more formal and tangible needs to be put in place with more specific guidelines on a regional, and seasonal or annual basis. What looks promising for this area is a new form of long-lead forecasting using statistical regression modelling (Brown et al., 2004).

Management strategies must be continually refined by new information in an adaptive framework (Williams et al., 2003b). Policies that integrate social and ecological needs across administrative boundaries and broad landscapes are required (Dombeck et al., 2004). At the same time, we must recognize that different landscapes have different fire regimes which require different fire management policies. As no single fire regime or spatial scale is suitable for all species, treatments must be tailored to specific sites if we wish to restore or maintain ecological integrity (Burrows, 2008; Dellasala et al., 2004; Russell-Smith, 2002). More research is required into these complex relationships in our pursuit to limit the most destructive aspects of fires, while preserving their social, economic and ecological benefits.

The Desert Knowledge Cooperative Research Centre (DK CRC) is a national research network, linking Indigenous and local knowledge with science and education, to improve desert livelihoods. Project ‘Desert Fire’, of which this research forms a part, is fundamental to the principles of the DK CRC. Effective fire management is dependent upon collaboration and cooperation between stakeholder groups and residents. It is about providing information and skills development to people living in remote localities in order for them to develop better and more secure livelihoods. By using fire in an appropriate manner, not only can we protect their livelihood and reduce the cost and impact of wildfires, they can use appropriate fire management practices to assist with and enhance productivity of existing and potential industries e.g. pastoralism and bush tucker. Improved fire management has long-term benefits to biodiversity, and direct benefits to associated eco-tourism dependant endeavours.

1.2 Aims

This project provides an objective, continental and regional perspective, on fire regimes across the arid and semi-arid regions of Australia for the period 1998 to 2004, using data derived from the National Oceanographic and Atmospheric Administration’s (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite sensor. A fundamental aim is to describe the different spatial and temporal patterns of recent fire regimes. Another is to increase our understanding of their causes through statistical analyses, to help explain these different patterns in an effort to increase our forecasting capability. This research will help to gain a predictive understanding of the spatial and temporal pattern of risk of large uncontrollable fires, which can assist in the effort of pro-active management. Clearly, validating the fire data is also an important component of this research.

1.3 Objectives

To achieve the aims of this dissertation, a number of specific objectives were established. The structure of the dissertation is such, that generally each objective is addressed sequentially in a separate chapter. Thus, most of the following objectives provide an overview of the chapters of this dissertation. The first chapter provides the context for this dissertation. Chapter 2 provides background on the causes, distribution, and impacts of fire and management options in general. It also discusses current legislation, policies and plans in Australia. The next chapter discusses mapping, monitoring and modelling fire events at both a global and regional scale. Chapters 4-6 present the results of my analysis within arid and semi-arid Australia, and have been written as journal articles, and as such some information may be repeated (Turner et al., 2008, 2009a, b). The final chapter draws together the conclusions reached in this dissertation, and discusses some future directions.

Objective 1: Context

- Set the context of this dissertation.
- State the aims and objectives.
- Define the study area and its characteristics.

Objective 2: Background on fire

- Provide an overview of the causes and distribution of fires globally and in Australia.
- Describe their environmental and socio-economic impacts, both positive and negative.
- Give an overview of the options available for managing fire, and how these are and have been used in arid and semi-arid Australia in particular.
- Describe current legislation, policies and plans in the various mainland states of Australia.

Objective 3: Background on mapping, monitoring and modelling fire

- Explain how remote sensing systems are used for active fire (fire hotspot) detection, burned area mapping, and monitoring of individual fire events.
- Explain the components which make up a fire regime, and the techniques employed to measure them.
- Describe the research into defining and analysing fire regimes in arid and semi-arid Australia, using prehistoric, historic and contemporary records.
- Discuss the difference between physical-statistical and statistical fire modelling.
- Provide an overview of the decision Support Systems and predictive models available for fire management, with a particular emphasis on Australian systems, and limited examples and discussion of systems developed overseas.

Objective 4: Validation and quality assurance

- Use available mapped fire scars from higher resolution Landsat imagery, and ground truth data where available, to validate the NOAA-AVHRR derived fire hotspot (FHS) and fire affected area (FAA) data, in selected areas of arid and semi-arid Australia.

Objective 5: Summary statistics

- Using statistical analysis within a GIS (Geographic Information System) framework, describe the broad patterns of fire
    - distribution
    - extent
    - seasonality and

    - frequency

  in arid and semi-arid Australia as a whole, and also by climatic regions, for the period 1998 to 2004.
- Examine the broad scale relationship between antecedent rainfall and area burnt.
- As part of this analysis produce continental and regional (by IBRA - Interim Biogeographical Regions of Australia (Thackway and Cresswell, 1995)) maps for this period to highlight the annual variability of fire and the extensive wildfires associated with the 1999-2001 period of above-average rainfall.

Objective 6: Explain and predict

- Assemble a comprehensive spatial and temporal database of factors (climatic, edaphic and anthropogenic) influencing fire regime.
- Perform exploratory analysis (using geo-statistical and regression analysis) of climatic, edaphic and anthropogenic factors affecting fire regime to elucidate the relative strength of influence and predictive capability of these variables on fire regimes in arid and semi-arid Australia, at both a continental and regional level.

Objective 7: Conclusions

- Summarise the conclusions drawn from this dissertation.
- Outline some future directions.

1.4 Study Area

This study area is delineated by the Australian Bureau of Meteorology's 'dry climate' zones, using a modification of Köppen's classification of world climates (figure 1.1). These zones are defined on the basis of there being an excess of evaporation over precipitation, which is determined from the mean annual temperature and the mean annual rainfall over 30 years (Stern et al., 2000). They are bound by median annual rainfalls of about 250 mm in the south, up to 800 mm in the north and 500 mm in the east. This rainfall is highly erratic, with extremes of long dry periods and flooding deluges.

These arid and semi-arid lands, often referred to as rangelands, occupy 70% of Australia (5.5 million km^2) and are inhabited by less than 3% of the population (about 500,000 people) (Brown et al., 2008). There are 6 towns with a population between 20,000 and 30,000, 100 other settlements with over 1,000 people and a further 150 population centres with up to 200 people. The remainder of the population live in hundreds of smaller Aboriginal communities and outstations, and on pastoral properties.

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Figure 1.1Major climate groups

Based on Stern et al. (2000)

Soils, predominantly sands, massive and structured earths, loams and cracking clays, are characteristically very infertile over vast areas (BRS, 1991). Natural vegetation covers the majority of the area, with hummock grasslands (such as Feathertop Spinifex *Triodia schinzii,* Hard Spinifex *Triodia basedowii,* and Soft Spinifex *Triodia pungens*) most often associated with the sands. The other major vegetation types are tussock grasslands (such as Mitchell grasses *Astrebla* spp. and Bluegrass *Dicanthium* spp.) and acacia woodlands and shrublands (such as Mulga *Acacia aneura*) (National Land and Water Resources Audit, 2001). There are a small number of large native mammals, but large numbers and diversity of lizards, ants and termites, while pastoral lands support sheep and cattle.

Fire is characterised by pulses of large intense wildfire following above average rainfall in preceding years (Allan and Southgate, 2002; Edwards et al., 2008). People have different ecological, cultural and economic priorities and outlooks about fire and its management (Edwards et al., 2008). The major stakeholders in arid and semi-arid Australia are pastoralists, Aboriginal communities, and conservation park managers. Others include town dwellers, tourist operators, mining companies, a small number of horticulturalists, and federal, state and local governments.

1.5 Stakeholders

While some broad generalisations are made below, Allan (2003) recognises the need to identify variations in the use of fire, and attitudes towards it, between the states and across the range of climatic regions. He also calls for further descriptions of the differences in the historical spread of pastoralism, continuing changes in land management and shifts in Aboriginal populations on a regional basis.

1.5.1 Pastoral

Pastoral lands account for ~50% of arid and semi-arid Australia (Stewart et al., 2001), producing mostly cattle in the north and sheep in the south. They have a diverse range of vegetation including grassy plains, open woodlands with a mix of grasses and acacias (mostly mulga), and some areas of acacia woodlands with minimal understoreys (National Land and Water Resources Audit, 2001). Grazing by animals, including termites, generally keeps the fuel loads low, except after extended periods of widespread rain when growth can far exceed consumption. These areas have the least frequent incidence of fires in desert Australia, and return intervals can be 30 to 50 years (Hodgkinson, 2002).

Pastoral lands are managed chiefly for sustainable animal production (Myers et al., 2004). Fire, together with control of stocking rates, is the major tool available for land management in the rangelands (Fisher et al., 2004). Although fire is often totally suppressed under pastoral management to protect pasture and other assets (Edwards et al., 2008; Griffin et al., 1983), it has been used as a tool by landowners to a limited extent in recent years.

Controlled, lower-intensity fires are sometimes used to clear land, improve pasture biomass or to help manage woody weeds. Fire is also used for fuel hazard reduction and creating protective fire breaks to protect life and property. Occasionally a patch mosaic, with an appropriate frequency of burning, is used to promote biodiversity (Craig, 1999; Letnic, 2004; Myers et al., 2004; Vitelli and Pitt, 2006).

1.5.2 Aboriginal

The majority of Aboriginal lands are currently in the NT, comprising ~20% of the study area, while most Vacant Crown Land is in WA and amounts to a further 15% (Stewart et al., 2001). These lands equate roughly to the spinifex-covered sand plains, dune fields and stony deserts which are too unproductive and variable for livestock, but are home to a rich termite and lizard fauna (BRS, 1991; National Land and Water Resources Audit, 2001). Spinifex grasses are highly flammable, and these grasslands are most regularly and extensively burnt, resulting in the almost complete destruction of above-ground vegetation. In the years immediately following fire, ephemeral grasses and herbs form the dominant vegetation. Spinifex again becomes the dominant species after about

5 years of average rainfall (Letnic et al., 2004; Wright and Clarke, 2007a). Fuel loads accumulate as the hummocks grow in association with the variable rainfall. This limits the interval between fires, which can range from less than 3 years to over 30 years (Allan and Southgate, 2002). The flammability of spinifex grasslands increases with time, not only due to increasing cover and weight of flammable vegetation, but also due to decreasing moisture content and an increasing proportion of drier dead material accumulating in the hummocks (Burrows et al., 2006c).

Indigenous land is managed for sustainable harvesting of resources (implying biodiversity conservation on a landscape scale), and for cultural and heritage purposes (Myers et al., 2004). Today, Aboriginal communities largely exist by subsistence activities, harvesting natural resources from the land; some small business enterprises such as painting, bush-tucker, and small scale culturally based tourism enterprises; and government payments. Pastoralism is practised in a number of areas on Aboriginal freehold land and by Aboriginal people on land which they hold under pastoral leasehold title (Rose, 1995).

Traditionally, Aboriginal communities used fire in hunting and “fire-stick” farming, as well as for cooking, warmth, communication, ease of travel and ceremonial reasons (Bird et al., 2003, 2005; Bowman, 1998; Fensham, 1997; Latz, 1995). Although fire management is still culturally important today, the opportunities for getting out on country to burn are constrained (Edwards et al., 2008). This being said, roadside ignitions by Aboriginal travellers were responsible for many of the fires in central Australia during the 2000-02 fire event, causing considerable animosity from pastoralists (Edwards et al., 2008). Wildfires are often left to burn themselves out, especially in more remote areas.

1.5.3 Conservation

Conservation or national parks constitute ~4% of the study area (Stewart et al., 2001). Many are located in the ranges with their many gorges and gullies. Spinifex communities dominate the hills and ridges, while non-spinifex vegetation dominates the flatter areas. Twenty years ago, over half of Australia's species of endangered mammals, more than a third of its threatened bird species and about one tenth of its threatened plant species occurred in the arid and semi-arid lands (Morton et al., 1995), and the decline is continuing (Woinarski and Fisher, 2003). The parks and reserves are refuges for animals and fire sensitive plant species. They are managed chiefly for biodiversity (Myers et al., 2004), but are also important scenic locations for tourism. Elevated positions are quite prone to lightning strikes, which can cause wildfires given an adequate fuel load and fuel continuity. On the other hand, the floors of deep gorges, steep rocky hillsides, and scree slopes are habitats that may offer almost complete protection from fire.

Fire management is aimed at protecting physical assets, cultural sites and human life, as well as protecting and enhancing biodiversity (Duguid et al., 2009; Edwards et al., 2008; Gill et al., 2002a; Keith et al., 2002). Prescribed burning is sometimes employed by park managers, to help prevent large uncontrollable wildfires. Occasionally, a patch mosaic, with an appropriate frequency of burning, is used to promote biodiversity. Some parks also conduct experimental burns, aimed at researching and describing how fire behaves in different fuel types and under different regimes.

1.5.4 Urban

There are a number of large towns, and many small towns, service centres and Aboriginal settlements scattered through arid and semi-arid Australia, as already stated, as well as increasing numbers of tourist accommodation and campsites.

Wherever people are gathered, wildfires may be caused by accident or neglect. Unfortunately, there are also those fires lit by arsonists for a variety of reasons (Bryant and Willis, 2006). Suppression tactics will normally be performed on these fires in an effort to protect life and property. Controlled fires may also be lit for reducing bushfire hazard by reducing fuel load, creating protective fire breaks, burning rubbish, cooking and heating.

Chapter 2

FIRE AND ITS MANAGEMENT

2.1 Causes

Even before the first use of fire by humans, (possibly as early as 1.5 million years ago and certainly by 230,000 years ago (James, 1989)), it was shaping the landscape structure and ecosystems through ignitions by lightning (Beerling and Osborne, 2006; Orians and Milewski, 2007; Outcalt, 2008; Vanniere et al., 2008; Williams et al., 2002).Wildfires are a natural phenomenon essential to the functioning of many ecosystems worldwide, and have played a critical role in the natural environment of our planet for at least 350 million years (Beerling and Osborne, 2006; Glasspool et al., 2004, 2006; Scott and Glasspool, 2006; Uhl et al., 2007).

Today the majority of fires worldwide, (possibly as many as 90-95%), are caused by human activities, with most being intentionally lit (Levine et al., 1999; Tansey et al., 2008). Indigenous tribes have used fire over the centuries to flush out animals during a hunt, for promoting green flush to attract animals, or to promote the abundance of food plants, for signaling, to 'clean' the country, increase visibility, or eliminate pests, and for cooking, heating and protection (Berkes and Davidson-Hunt, 2006; Bird et al., 2005; Burrows et al., 2004; Mistry et al., 2005; Natcher et al., 2007; Whitehead et al., 2003). Fire is used by farmers in land and forest clearing, landuse change, slash-and-burn agriculture, and to help combat weeds (Craig, 1999; De Mendonca et al., 2004; DiTomaso et al., 2006; Ketterings et al., 1999; Miettinen et al., 2007; Morton et al., 2006; Varma, 2003). Prescribed fuel hazard reduction burning is a form of land management, employed by forest and park managers, to help prevent large uncontrollable wildfires (CALM, 2001; Caprio et al., 1997; Finney et al., 2005). Fire is also employed for protection of biodiversity (Bond and Archibald, 2003; Granstrom, 2001; Howe, 1994; Sladek et al., 2008). Regeneration burning is sometimes employed after timber harvesting, before replanting occurs (Baker et al., 2004). In recent years, the pressure of increased population growth in suburban and tourists areas, has led to an increase of fires caused by accident or neglect, and by arsonists (Levine et al., 1999; San-Miguel-Ayanz et al., 2002).

In sparsely populated arid and semi-arid Australia, it is difficult to know for certain how many fires are started by lightning and how many by humans, as many are not attended, or reported in official statistics.

Recent statistics from fires 'attended' by the Department of Environment and Conservation in all of Western Australia show that, while lightning fires still occur regularly, most fires are started by people, either accidentally or deliberately. Each year they respond to more than 500 wildfires. Lightning causes about 22% of these fires; accidental causes are about 13%; deliberately lit (arson) fires account for 43%, escapes from burning operations on Departmental managed land account for less than 2%, and unknown and other causes account for 20% (Department of Environment and Conservation, 2008). However, in the spinifex grasslands of Western Australia, most fires are started by lightning, although human-caused ignitions are significant near settlements, on pastoral leases and along travel routes (Burrows et al., 2006c).The Western Australia Environmental Protection Agency fire review reports that most fires in the Kimberley and Pilbara Regions in the north are lit by people, accidentally, maliciously or deliberately for a range of purposes, with a smaller proportion caused by lightning; while most of the wildfires in the Goldfields region in the south are predominantly started by lightning (EPA, 2006a).

In central Australia (the southern half of the Northern Territory), 58% of the 759 records of reported wildfires between 1970 and 1980, attribute the cause to lightning (Griffin et al., 1983). But there has been an increase in human ignitions by roadsides in recent times, due in part to changes in population demographics, and increased accessibility to remote areas. Edwards et al. (2008) report that roadside ignitions by Aboriginal travellers were a major source of fire in central Australia during the 2000-02 fire events, with and increase in these fires during the cooler months of April-August compared to the 1970’s fires.

In South Australia, the Country Fire Service deals with almost 2,000 rural incidents per year, with less than 10% reported as being ignited by lightning. About 10% of the incidents that they attend occur in the arid and semi-arid regions of the state (South Australian Country Fire Service, 2007).

2.2 Distribution

Vegetation fires occur worldwide, all year round. It has been estimated that fires annually burn 10-15 million hectares of boreal and temperate forest, 20-40 million hectares of tropical forests, and up to 500 million hectares (5 million square kilometers) of tropical and subtropical savannas, woodlands and open forests (Goldammer, 1995).

Dwyer et al. (2000) carried out the first global study of satellite imagery that used a long time series data set (18 months between 1992 and 1993) and a single processing technique. At AVHRR’s 1.1 km resolution, they estimated that half of the active fires detected were on the African continent and over 70% within the tropical belt. Fires were detected in more than 6% of the pixels over land during a 12-month period, and savanna grasslands accounted for over one third of this area.

Since 2000 daily global active fire detection has been provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. Results from the first six years of data show that more than 30% of the land surface has a significant fire frequency. The densest areas of fire occurrence were mainly in the tropical belt, (including tropical Africa, Central and South America, Australia and SE Asia), and the south-boreal Asian fringe (Ukraine to far east Siberia) (Chuvieco et al., 2008a).

A recent analysis of global area burnt, using a single algorithm with 1 km resolution SPOT VEGETATION data, estimated that between 3.5 and 4.5 million square kilometers of vegetation burnt annually in the seven year period 2000-2007 (Tansey et al., 2008). The values are reported for 16 vegetation types. The algorithm underestimates burnt area in low vegetation cover seen in semi-arid Australia and Africa, as well as many small agricultural fires.

On average, 45,000 fires take place in the five southern European Union (EU) countries every year, burning half a million hectares of the landscape (San-Miguel-Ayanz et al., 2002). In the USA over the last 10 years, an average of 13,857 prescribed fires have burnt almost 1 million hectares annually, while an additional 80,000 wildfires burnt over 2.5 million hectares on average annually (NIFC, 2008b).

A study of Australia using NOAA-AVHRR data from April 1998 to March 2000 showed that at least 13% (over 1 million square kilometers or 100 million hectares) of the continent was burnt in the two-year study. Large fire scars were mapped in the north of Australia, especially in autumn and winter, and small fire scars in the south of Australia with very few in South Australia, New South Wales, Victoria and Tasmania (Craig et al., 2002). While this was a period of low fire activity in central Australia, fires in spinifex grasslands can frequently exceed 10,000 km^2 (1 million hectares) (Allan and Southgate, 2002).

Whether natural or anthropogenic in origin, controlled or uncontrolled, fire can have a significant impact on terrestrial, aquatic and atmospheric systems at local, regional or global scales; and also affect human societies, economies and politics.

2.3 Environmental Impacts

Fires result in important ecological benefits to many ecosystems. They influence plant community development and biological diversity, nutrient availability and soil productivity (Bisson et al., 2003; Bond and Keeley, 2005; Certini, 2005; DeLuca and Sala, 2006; Dombeck et al., 2004; Fearnside, 2008; Levine et al., 1999; Parr et al., 2007). Many of Australia's unique and highly diverse range of plants and animals are dependant upon different fire regimes for their survival (Allan and Southgate, 2002; Bond and Keeley, 2005; CALM, 2001). "Aboriginal burning was important in creating habitat mosaics that favoured the abundance of some mammal species and in the maintenance of infrequently burnt habitats upon which the survival of specialized fauna depends" (Bowman, 1998).

Fires can, however, cause tremendous adverse impacts on the environment. These include issues such as loss of habitat for threatened and endangered plant and wildlife species, removal of litter cover, changes to microbial activity, water quality, catchment water yield and rock weathering, and modifications in the soils structure, hydrological properties and nutrient status (Barlow et al., 2006;

Certini, 2005; Ice et al., 2004; Letnic et al., 2005; Shakesby and Doerr, 2006; Townsend and Douglas, 2004). Secondary effects such as erosion, surface water run-off, landslides, or extended flooding can also occur (Ahern et al., 2001; Ice et al., 2004; Rulli and Rosso, 2007; Shakesby and Doerr, 2006).

A major consequence of fires is their potential effects on climate change. Biomass burning is now recognised as a significant contributor to global carbon dioxide and tropospheric ozone emissions (Field et al., 2007). The relationships are very complex and differ in various ecosystems, and can result in either positive or negative feedbacks (Field et al., 2007; Goetz et al., 2007; Jones and Cox, 2005).

2.4 Socio-Economic Impacts

Fire is widely used as an effective tool in land management (as discussed in section 2.1), but the side effects can be devastating if misused or uncontrolled. In recent decades there has been a change in fire patterns, as humans have introduced burning into areas not normally burnt naturally, while suppressing fire in other areas (Levine et al., 1999). Other factors affecting this change include widespread logging, road building, habitat fragmentation, urban development, livestock grazing, and, more recently, climate change (Aiken, 2004; Dellasala et al., 2004). In some developed countries, an increase in wildfires is also partially due to changes in social attitudes, which have lead to a decrease in planned burning, which in turn leads to an increase in fuel hazard. Over a number of decades this has led to an increase in uncontrolled wildfires globally.

The catastrophic wildfires of 1997 and 1998 brought this to the attention of the world, as they swept across South East Asia, South and Central America, Europe, Russia, China, Australia, the USA and Canada. The severity of many of them is attributed to drought conditions caused by El Nino (Moore, 2001; San-Miguel-Ayanz et al., 2002). During these fires more than 22 million hectares of land were burnt worldwide, of which one third was non-forested and comprised mainly agricultural land. Indonesia alone accounted for 9.5 million hectares, half of it forested, at an economic cost of between US$ 5 and US$ 10 billion (Moore, 2001).

The adverse consequences of fires can come directly from the fire itself or from the smoke and haze produced by it. The economic costs of direct fire damage include destruction of timber, agricultural land, food and raw materials, businesses and homes and fire fighting costs. There are also economic costs associated with loss of water supply, erosion control, soil and nutrient loss, loss of natural vegetation and wildlife habitats, and greenhouse gas emissions (Aiken, 2004; General Accounting Office, 2003; Koe et al., 2001; Levine et al., 1999; Moore, 2001; San-Miguel-Ayanz et al., 2002). These costs do not of course take into account the loss of life associated with the fire itself and efforts to control it.

The impacts of smoke and haze occur on a number of different levels also. From a health and safety point of view, smoke and air pollution can cause serious health problems for millions of people during large fires, as they can be exposed to high levels of fire-produced gases and particulates for weeks at a time (Hu et al., 2008; Johnston et al., 2007a; Koe et al., 2001; Kunzli et al., 2006; Yokelson et al., 2007). Poor visibility, on the other hand, can affect national and international air traffic and has been responsible for accidents on land, sea and air (Aiken, 2004; McKenzie et al., 2006). Smoke and haze also have adverse economic impacts through increased health care treatment costs (both short and long term), and declines in tourism and industry production (Aiken, 2004; Levine et al., 1999; Moore, 2001).

2.5 Management

We have a responsibility to manage fires in order to enhance their positive aspects and limit the negative. As already alluded to, fire can be managed through suppression of wildfires (accidental fires), or by prescribed (planned) burns for fuel hazard reduction, sustainable land management, or ecosystem restoration. The way fire affects our landscape has changed over the centuries as our perception about fire, and our management of it, have altered.

2.5.1 Traditional Management

For more than 10,000 years, the frequent use of fire by Native Americans in the western United States shaped the structure and composition of frequent-fire forests (from dry ponderosa pine forests to moist, mixed-conifer forests) (Dellasala et al., 2004; Keeley, 2002; Murphy et al., 2007). Practices included burning to enhance the quantity and improved the qualities of plant species used for food, medicine, ceremonies, and baskets; and using fire to drive game and open the forest to increase visibility and improve foraging. This resulted in open forests of large, old trees with a dense ground cover of grasses and forbs (Murphy et al., 2007). It is estimated that about 10 times more landscape was burned, 8 times more biomass was consumed, and 7 times more emissions were produced annually in the pre-industrial conterminous United States than at present (Leenhouts, 1998).

Indigenous peoples have also been using fire in the cerrado (savannas) of Brazil as a form of management for thousands of years (Denevan et al., 1984; Mistry et al., 2005). They practice a system of shifting cultivation (known as succession management, swidden or slash-and-burn) that uses fire as a way to clear land and initiate ecological cycles that provide food and other materials. This practice produces a mosaic of burned and unburned patches in the landscape. The Bora people of the Peruvian Amazon burn a forest patch and plant a succession of crops from annuals and root crops to bananas to tree crops, mimicking natural succession. Some 30 years later, the patch has grown to look similar to the original forest but still yields useful products for the Bora (Denevan et al., 1984).

Fire was also an indispensable tool used for short and long-term gains in traditional Aboriginal economies. “Fire-stick farming”, as it has been dubbed, was used “purposefully, frequently and regularly” across the landscape for a variety of natural resource and cultural management purposes, but mainly to acquire food (Bowman, 1998; Russell-Smith et al., 2003a). It produced a landscape mosaic of small burnt patches of vegetation at different stages of post-fire succession. This affected the evolution of the Australian biota, but it is not clear whether or not Aborigines were aware of the long-term ecological consequences of their use of fire (Bowman, 1998; Burrows et al., 2004; Price and Bowman, 1994).

2.5.2 Suppression

In the late 1800s and early 1900s, a combination of slash left behind by logging and drought, led to a series of fires that devastated the American West and Midwest. Society began to view fire as a dangerous force to be suppressed and contained at all costs, and a policy of “all fires out by 10am” was formally adopted in 1935 (Dombeck et al., 2004; Murphy et al., 2007). During the 1930s to 1970s the area burned decreased in the USA under this new management regime (Dellasala et al., 2004). A similar strategy was adopted by many other cultures around the world who saw fire as a ‘catastrophe’ (Kauffman, 2004).

While fire would have been used by Australian pastoralists in the early days to clear new land, by the early 1900s they too viewed fire as a threat to their grass resources, and attempted to suppress wildfires whenever possible. In the early 1980s fire management practices in central Australia were still aimed primarily at wildfire suppression (Griffin et al., 1983).

Decades of these total fire suppression policies, along with other anthropogenic modification such as land use changes, logging, road building, habitat fragmentation, urban development and livestock grazing have altered the fuel loads and fire regimes of many areas around the world. Gone are the many smaller fires that burned at low intensity (Dellasala et al., 2004; Dombeck et al., 2004; Kauffman, 2004; Murphy et al., 2007). In the western United States, forests that historically had high fire return intervals have become overstocked with fuels, while some rangelands have changed composition from fire maintained grasslands to grazed shrublands (Miller and Yool, 2002).

In Australia, coupled with the increase in pastoralism, was the departure of Aboriginal people and their traditional fire regimes from many regions of the country, leading to an accumulation of fuels over vast areas. This has changed the landscape from a fine-grained mosaic of small burnt patches of different ages, to a simpler mosaic consisting of either vast tracts of long unburnt vegetation, or vast tracts of vegetation burnt mainly by large and intense lightning-caused wildfires (Burrows et al., 2004).

2.5.3 Prescribed Burning

Throughout the world since the 1980s, there has been a dramatic increase in the application of fire for land-use change and in the number, intensity and extent of wildfires (Ahern et al., 2001; Dellasala et al., 2004). With the increase in severe wildfires it has become important to use fire itself as a management option for fuel modification and ecosystem restoration. Over fifty years of research has led to considerable advances in our knowledge of fire ecology and management in Australia, but most particularly the last two decades (Gill et al., 2002a; Keith et al., 2002).

2.5.3.1 Fuel Hazard Reduction

Prescribed burning has been used mainly for the reduction of fuel loads in an attempt to reduce wildfire hazard. Studies show that this fuel reduction generally lessens the intensity, size and damage of wildfires and so can aid in their suppression (Finney et al., 2005; King et al., 2008b; Martinson and Omi, 2008). But the implications of such practices are not yet fully understood. The optimum timing and spatial pattern of burning for different environments needs to be better understood, and practical management guidelines drawn up (Fernandes and Botelho, 2003).

Policy changes that are intended to prevent or contain fires can pose significant risks to the integrity of ecosystems if applied inappropriately (Dellasala et al., 2004). In the United States, Schoennagel et al. (2004) warn that a model for fuel reduction based on dry ponderosa pine forests is being applied indiscriminately across all Rocky Mountain forests. They claim this “one size fits all” approach is unlikely to be effective and may be detrimental in some areas.

In areas of Arnhem Land the European management objective is to burn in the first half of the dry season before the grass fuel loads become heavy. This, however, appears to have triggered a positive feedback cycle between fire frequency and flammable grass fuels which can be very difficult to break once established (Bowman et al., 2004).

While hazard reduction burning has been adopted in many tropical and temperate regions of the country, it has not been used in the arid and semi-arid regions to the same extent (Myers et al., 2004), although burning (in particular aerial burning) is the only practical method of fuel hazard reduction in many of these remote areas.

2.5.3.2 Sustainable Land Use

Fire still plays an important role in agriculture and forestry throughout many parts of the globe including Africa (Angassa and Oba, 2008; Baker, 2000; Eriksen, 2007), Indonesia (Mudita, 2000; Russell-Smith et al., 2007a), Bolivia (McDaniel et al., 2005), India (Schmerbeck and Seeland, 2007) and Australia (Bortolussi et al., 2005). In parts of Indonesia for example, it is still the most efficient tool available for land preparation, soil fertility improvement, and weed and pest control

(Mudita, 2000; Russell-Smith et al., 2007a). Today much burning is unmanaged and uncontrolled, but sound fire management is necessary if agricultural development is to be sustainable.

A review of arid and semi-arid Australia in the mid 1990s revealed that 42% of these lands were suffering from severe degradation or desertification, due in large part to unsustainable land use practices (Ludwig and Tongway, 1995). This is primarily through the loss of perennial grasses from grasslands, savannas, and open woodlands, often with a replacement by inedible woody shrubs. It is occurring most extensively in the pastoral zone, due mainly to grazing pressure in conjunction with drought, fire and other factors, such as past policies and management. But it also extends outside the pastoral zone due to the impact of feral animals and changed fire regimes (Ludwig and Tongway, 1995; Morton et al., 1995; Pickup, 1998). Two national programs, Drought Alert and Landcare, have been established to tackle this problem.

Fire is the only practical means of controlling woody weeds in these areas, as they are not consumed by livestock. Fire also releases nutrients for the development of grasses. Individual pastoral managers must decide whether to use grass biomass for short-term gains in animal production, or as fuel for prescribed burns to manage woody weeds and/or to release nutrients for the longer term. This requires managing their stocking levels to allow sufficient build up in the fuel load to enable the system to burn (Perrings and Walker, 1997).

In the savannas of northern Australia, there are now a number of regionally-based cooperative projects, involving traditional owners, pastoralists, government and commercial agencies, that are now educating communities and implementing appropriate fire management for sustainable landuse (Russell-Smith et al., 2003a). In the arid and semi-arid regions of the country however, although knowing the utility of prescribed fire for reshaping vegetation composition and structure for the benefit of livestock production, pastoralists have struggled with questions concerning the correct fire regime (intensity, frequency and spatial pattern of burning), control of post-fire grazing, and the economics of fire management (Craig, 1999; Hodgkinson, 2002).

2.5.3.3 Ecosystem Restoration

Historically, the primary focus for fire management planning globally has been protection against wildfire, particularly for life and property. Conservationists have long recognised that fire regimes have been a major driving force in the maintenance of biodiversity in many ecosystems. Land managers are now slowly beginning to reintroduce fire as a functional component of ecosystems, with an increased emphasis on conservation values (Andersen et al., 1998; CALM, 2001; Clarke, 2008; Fule et al., 2004; Granstrom, 2001; Moore et al., 2006; Morley et al., 2004). But there is often confusion or disagreement as to the desired outcomes (Klenk et al., 2008), and lack of sound ecological knowledge to implement these goals.

Following decades of development and testing, there is now a formalized system for fire-prone savanna ecosystems in southern African conservation areas. This uses prescribed burning to produce a diverse fire regime and spatial heterogeneity of fire patterns in order to conserve biodiversity (Bond and Archibald, 2003; Brockett et al., 2001; Van Wilgen et al., 2004).

In America, Sierra Nevada National Parks integrate hazard, risk, and value criteria within a framework of GIS to identify high priority areas most in need of burn treatment to optimize the use of limited funding. Within this model, the longer a time interval exceeded the maximum historic fire interval without a fire, the higher the priority rating for returning fire to this area (Caprio et al., 1997).But generally in America, while there is, in theory, a recognised ecological need to reintroduce fire, in practice very few fires are allowed to burn out naturally (Dellasala et al., 2004).

Recently there has been a shift in Australian government legislation away from the historical emphasis on prevention and suppression of fire, aimed at minimising loss of life and property, towards plans that specifically incorporate biodiversity conservation. The Biodiversity Theme Report for the Australia State of the Environment Report 2001 reviewed the fire policies then in operation in each state (CSIRO, 2001a). Each addressed ecological and biodiversity conservation issues, but to very varying degrees. The report stated that “the paucity of ecological data relating to fire regimes has meant that consideration of biodiversity in fire management has been minimal”. While, in theory, it appears that management is moving towards fire as a tool for ecological health, the lack of sound scientific knowledge has hampered them.

Arid and semi arid Australia has been affected with extinctions and contractions of range among its native biota since European settlement (Morton et al., 1995; Noble and Grice, 2002; Pickup, 1998). Two hundred mammal species have become extinct in the last 200 years. Broad scale losses have been reported for a high proportion of birds, and many plants have also suffered substantial declines. It is likely the same is happening with reptiles and invertebrates, but there is a lack of historical records to compare against. Over half of Australia's species of endangered mammals, more than a third of its threatened bird species and about one tenth of its threatened plant species occur in the desert semi-arid and arid lands. And the decline is continuing (Morton et al., 1995; Woinarski and Fisher, 2003). This loss of biodiversity is due to a combination of factors including clearing, grazing, altered fire regimes, the spread of pests and exotic plants, mining, pollution and climate change (Benson, 2001; Wilson and Friend, 1999; Woinarski and Fisher, 2003). Prescribed fire is now recognized as one of the few cost-effective tools available for maintaining that biological diversity in our arid and semi-arid lands (Noble and Grice, 2002).

There are a number of principals and approaches for the use of fire in biodiversity management (Burrows, 2008). The first of these is the concept of the fire regime, i.e. how repeated fires affect an area over time (Gill et al., 2002a). Gill (1975) described the elements of fire regimes as frequency, intensity, spatial extent, seasonality, and type of fire (e.g., ground, surface, or crown fire). While conservation management sometimes seeks to attain the ‘natural’ fire regime of an area, this is impossible to define for most of arid and semi-arid Australia, due to the lack of historical records. It is more productive to look at how species, populations and communities respond to fire, in order to develop an ‘ecologically appropriate’ regime, which will maintain the viability of the ecosystem in question.

But extinctions and species decline may still be likely if fire regimes of relatively fixed intensity, frequency and extent prevail without interruption. Sometimes a diversity of fire regimes may be required in order to maintain native biodiversity (Burrows, 2008). This means that over time, there may be a need to implement fires of variable intensity, frequency and size, within critical fire regime thresholds, for an area. These thresholds mark a change from high species diversity to low species diversity, thus separating desirable and undesirable fire regimes (Bradstock and Kenny, 2003; Keith et al., 2002; Tasker et al., 2006).

Another key concept is that of the functional group. This is a group of species that respond in a similar way to a disturbance, such as fire. This enables us to research a subset of the group, and then generalise and predict the impact of particular fire regimes on the relative abundance of the group in general (Andersen, 1995; Bradstock and Kenny, 2003; Gill et al., 2002a; Keith et al., 2002; Tasker et al., 2006). The best know of these are the “sprouter/non-sprouter” groups of Gill (1975), and the “vital attributes” scheme of Noble and Slatyer (1980). Functional group analysis is now commonly used in studies of plant responses to different fire regimes (Boer and Smith, 2003; Bradstock et al., 1998; Bradstock and Cohn, 2002; Bradstock and Kenny, 2003; Cummings et al., 2007; Knox and Clarke, 2006; Wright and Clarke, 2007a; Wright and Clarke, 2007b). However, other than the ant functional groups developed by Anderson (1995) (Andersen et al., 2002; Andersen et al., 2007; Gunawardene and Majer, 2005; Hoffmann, 2003), there has been little progress on developing functional groups for other fauna (Dawes-Gromadzki, 2007; Tasker et al., 2006).

In inland Australia, there has been uncertainty regarding the way to best manage fire frequency, fire size and fire patchiness in the spinifex grasslands to maintain biodiversity and ‘fire-sensitive’ plant and animal communities, protect pastoral activities and maintain cultural values (Allan and Southgate, 2002). This, however, is slowly changing.

2.5.3.4 Fire Regime Research Experiments

The ecological effects of different fire regimes are not yet fully understood around the world, but we are constantly learning more from the results of empirical fire regime experiments.

Kruger National Park, South Africa is possibly the only place with a rich history of manipulative fire-biodiversity experiments. Experimental burn trials were initiated in 1954 and are replicated in four representative savanna ecosystems (Govender et al., 2006; Higgins et al., 2007; Van Wilgen et al., 2004). Research on the effects of fire on fauna is fragmentary however (Parr and Chown, 2003).

In recent years there have been a number of fire experiments in the tropical savannas of northern Australia, to assess the influence of different fire regimes on the ecology of the region, in order to contribute to our understanding and management of biodiversity conservation in these regions.

Controlled, manipulative and replicated field experiments have been carried out at a number of different spatial and temporal scales:

- Munmarlary Station, Kakadu National Park.
  1973-1996. Two 1-hectare blocks (one in eucalypt open forest and one in eucalypt woodland), each with three replicates of four fire treatments (annual early dry season fire, annual late dry season fire, biennial early dry season fire and fire exclusion). (Andersen, 1991c; Bowman and Panton, 1995; Bowman et al., 1988; Russell-Smith et al., 2003c; Williams et al., 2003b).
  1997-2001. Further experiments were continued (Williams et al., 2003a).

- Kapalga Research Station, Kakadu National Park.
  1990-1994. Landscape scale blocks between 15 and 20 km^2 were subjected to one of four fire regimes (early, late, progressive and unburnt) in the savanna woodlands. Each fire regime was repeated at least three times. Baseline data was collected for up to 2 years before and one year after the five years of experimental fires. (Andersen et al., 1998; Andersen et al., 2005; Andersen et al., 2003; Andersen and Muller, 2000; Andersen et al., 2007; Blanche et al., 2001; Orgeas and Andersen, 2001; Pardon et al., 2003; Setterfield, 1997, 2002; Williams et al., 1999; Williams et al., 1998; Williams et al., 2003b).

- Victoria River Research Station, Kidman Springs, south-west of Katherine.
  1994-1998. Two sites of contrasting soil texture (clay, loam) on pastoral land in the Victoria River District in the semi-arid tropics of the Northern Territory. Both sites comprised 16 plots (each of 2.6 ha) subjected to seven different experimental fire regimes (unburnt, burnt in the early dry season at 2, 4 and 6 year intervals, and burnt in the late dry season at 2, 4 and 6 year intervals). A number of studies report on the response of vegetation. (Dyer and Mott, 1999; Hoffmann, 2003; Williams et al., 2003b; Woinarski et al., 1999).

- Territory Wildlife Park, east of Darwin.
  2004-2010+. Six different 1 ha fire treatment plots, replicated three times (i.e. 18 plots in total). The six treatments are: early burn every 1, 2, 3, or 5 years, late burn every 3 years, and unburned.(Dawes-Gromadzki, 2007; Parr et al., 2007).

There have also been some opportunistic and/or non-replicated experiments and monitoring programs at Solar Village near Darwin (Fensham, 1990; Woinarski et al., 2004), Weipa, western Cape York Peninsula (Bowman and Fensham, 1991; Woinarski et al., 2004), Kakadu National Park (Edwards et al., 2003; Russell-Smith and Edwards, 2006) and Kalumburu, North Kimberley (Vigilante and Bowman, 2004).

While many of the experiments concentrated on flora, there has also been some research into the effects of different fire regimes on fauna - ants at Munmarlary station (Andersen, 1991b); aquatic macrophytes, arthropods and vertebrates (Andersen et al., 2005; Andersen et al., 2003; Andersen and Muller, 2000), bandicoots (Pardon et al., 2003), and beetles (Blanche et al., 2001; Orgeas and Andersen, 2001) at Kapalga; birds (Valentine et al., 2007) and frilled necked lizards (Griffiths and Christian, 1996) at Kakadu National Park; ants (Hoffmann, 2003), and birds and reptiles (Woinarski et al., 1999) at Kidman Strings; vertebrates at Solar Village (Woinarski et al., 2004); the northern betong at Davies Creek in north-eastern Australia (Vernes et al., 2001); and soil macroinvertebrate (e.g. termites, spiders and coachroaches) at the Territory Wildlife Park (Dawes-Gromadzki, 2007).

These experiments have been very enlightening, although they have shown varied responses across studies. In general, they found that much of the savanna biota is highly resilient to fire, even of relatively high intensity. Riparian vegetation and associated stream biota, as well as small mammals, are notable exceptions to this general resilience. Species vary in their responses to fires, so no single fire regime can optimise all biodiversity outcomes. Fire frequency is a much more important factor than previously thought. The occurrence of relatively long fire-free intervals, which is currently lacking in many parks and reserves across northern Australia, is important for some flora and fauna species. But our understanding of these complex issues still remains inadequate. This has important implications for conservation management in these ecosystems.

The arid and semi-arid regions of the country have been under-investigated in terms of fauna and flora, due to remoteness and subsequent high travel and research costs (Gunawardene and Majer, 2005), and little has been published yet from some of the fire-biodiversity experiments that are being carried out in these areas. Unlike the tropics, the emphasis in the literature published to date is on fauna rather than flora.

- Oakvale pastoral property, near Nyngan, NSW.
  1977-1979. A shrub-invaded semi-arid woodland. Within an area of 108 ha, two areas of *Eucalyptus intertexta* and two areas of *Eucalyptus populnea* were delineated. Within each area 24 plots of 15 x 21 m were established. Plots were burnt with a low or high amount of fuel or not burnt, on one of 8 occasions (approximately 3 months apart) over 2 years. Hodgkinson (1991) reported on shrub recruitment response to intensity and season of fire.

- Uluru National Park, NT.

  1987-1990. The composition and abundance of small mammals (Masters et al., 2003) and reptiles (Masters, 1996) was examined in relation to succession, driven by fire and rainfall, on sandplains dominated by spinifex grassland. Three plots were located in an area burnt in 1976 by wildfire, and another three plots in an area burned in 1986 by experimental fires. Data on the species composition and abundance of the vegetation, mammals and reptiles were collected on 12 occasions between September 1987 and May 1990, with each sampling occasion being separated by a period of approximately three months.

- Watarrka National Park, 320 km south-west of Alice Springs, NT.

  1989-1990. As part of a larger study on fluctuations in rodent populations in response to rainfall, Southgate and Masters (1996) examined the short-term effects of fire on 3 species of rodents in sand-dune country dominated by hummock grasslands. Four plots were each burnt once, by one of two experimental fires.

- Queen Victoria Spring Nature Reserve, Great Victoria Desert, WA.

  1987-ongoing. A multi-taxon study (mammals, reptiles, invertebrates and vascular plants) on the effects of experimental fires on the flora and fauna of the Great Victoria Desert. Vegetation at all plots is dominated by spinifex. Prior to experimental burning the study site remained unburnt for over 30 years. Langlands et al. (2006) examined the effects of fire and rainfall on the spider assemblage. Five 25 ha plots were sampled. Four of the plots were each burnt once, until wildfire burnt all five plots in January 2003, and monitoring ceased on this project. The fires represented were: severe intensity summer wildfire, ‘patchy’ spring fire and long unburnt controls (>30 years since fire). Other research in the Great Victoria Desert includes that of Pearson (1991; 1993; 2004) and Pianka (1996).

- Gibson Desert Nature Reserve, WA.

  1998-ongoing. A long-term study area to look at the impact of fires in different seasons on reptiles and small mammals in spinifex grassland and mulga woodland. Gunawardene and Majer (2005) investigated the effect of a wild fire in 2001 on ant assemblages at six replicated 250 x 250 m plots, (already established for vegetation surveys and monitoring), in recently burnt and long unburnt areas of three main vegetation types.

- Simpson Desert, Queensland.

  1999-ongoing. Pastoral properties in the north-east Simpson Desert. Spinifex dominates sand-dune slopes and swales, and dune crests are dominated by shrubs. Ephemeral herbs and forbs are present after rain. Letnic (2003) performed a before - after - control - impact experiment to investigate the response of small mammals to the short-term (< 1 year) effects of patch-burning between August 1999 and June 2001. The experiment was replicated at three locations subject to differing rainfalls, with two 1 ha study grids remaining unburnt as controls, and two being burnt at each location. The areas burnt ranged from 1 to 3 ha. Letnic et al. (2004) also conducted a landscape-scale study investigating the responses of small mammals and lizards to fire in this area. In 1999 vertebrates were surveyed on 26 study grids, aged from 0 to >25 years post-fire, located at five sites. Letnic and Dickman (2005) compared the capture rates of small mammals (trapped between October 1999 and June 2001) in habitats regenerating shortly after fire (aged 1-5 years) and in long-unburnt habitats (aged >25 years). To unravel the effects of temporally and spatially variable rainfall on capture rates, the study was replicated at three locations spaced over 50 km apart that experience different rainfall regimes. Letnic et al. (2005) also examined the response of mammals to rainfall, predation and wildfire between 1999 and 2002. Following heavy rainfalls associated with the La Nina phase of the El Nino Southern Oscillation (ENSO) during 1999-2000, a pulse of primary productivity was stimulated, which prompted a rodent irruption during 2001, marked increases in the populations of native and introduced predators, and a subsequent extensive wildfire in 2001-2002, which burnt over 10,000 km^2 of the Simpson Desert. They used a before-after-control-impact study to investigate the effects of the wildfire on small mammals.

- Haasts Bluff Reserve, Alice Springs, NT.
  The effects of the large wildfires of 2000-2002 and preceding wildfires in the 1980s on spinifex sand-ridge plant communities were examined at 38 sites, to assess floristic differences among sites of contrasting time-since-fire, fire season and fire interval (Wright and Clarke, 2007a).

- Ngarkat Conservation Park, South Australia.
  The response of slender-billed thornbills to fire was studied in recently burnt, regenerating and mature heath (3, 10 and 22 years since fire respectively) between 1991-2002 (Ward and Paton, 2004).

In Wright and Clarke's study (2007a), fire season had little effect on most functional groups of plants, although seedlings of woody species were significantly more abundant following summer than winter fires. Recent short fire intervals also appeared to have little impact on the population dynamics of most functional groups. Long-term woody species abundances appeared to be affected by short fire intervals in the 1980s when repeated fires seemed to stimulate recruitment of some resprouting species. Spinifex is a relatively stable vegetation type in the face of landscape-scale fires, but localised shifts in the composition and structure of the plant community may occur under certain fire regimes.

The fauna studies above show that reptiles appear to show a successional response to fire that is mediated by vegetation succession. The effect of fire on arid and semi-arid zone mammal communities is less clear than that for reptiles. In a number of studies it was difficult to find definite trends. Others highlighted how different species responded differently to fire and vegetation succession. But the observed preference of species for recently burnt or long unburnt sites were not consistent throughout some studies, and contradicted the results of other experiments occasionally. Rainfall appeared to be the dominant driving force in some systems, where increased seed production prompts irruptions of some mammal species. Densities of slender-billed thornbills peaked seven years after fire, while densities were lower and less variable in unburnt mature heath. Therefore, in order to protect areas from which Slender-billed Thornbills can disperse into recently burnt habitats in Ngarkat, a spatial mosaic of habitats at different stages of post-fire succession is suggested.

Letnic and Dickman (2006) collated quantitative and qualitative data on climate, land-use, fire history and ecosystem dynamics to construct a chronology of processes threatening terrestrial mammal species over the last 150 years in their Simpson Desert study area. Irruptions of rodents, marked increases in the populations of native and introduced predators and extensive wildfires were associated with the La Nina phase of ENSO. The negative impacts of extensive wildfire on small mammals appear attributable to a loss of habitat for spinifex-dependent species and increased exposure to predation in burned habitats. Large rainfall events in arid Australia have been viewed traditionally as the ‘boom’ times that benefit wildlife and pastoral production. However, because of hyper-predation and the risk of wildfire, the years including and immediately following flooding rains should be identified as critical, or ‘bust’, periods for wildlife and conservation management.

These studies highlight the importance of long-term studies in explaining complex ecological processes, especially in highly variable arid regions. In the meantime, many suggest that a burning mosaic be considered as part of a management program for arid and semi-arid ecosystems. Letnic concluded that patch-burning regimes do not benefit small mammals directly, but are likely to increase the resilience of ‘fire-sensitive’ species that are dependent on dense spinifex by reducing the extent of wildfires, and also increasing the chance of maintaining potential refuges from predators (Letnic and Dickman, 2005; Letnic et al., 2005). While Hodgkinson (1991) concluded that the density and frequency of fire-recruited shrubs can be manipulated by selecting the season of, and environmental conditions for, prescribed fires.

Efforts to synthesize information from ecological research and expert opinion into management guidelines have been made in the last few years. Fire regime thresholds have been defined in some parts of the country, for major plant communities or for individual endangered or threatened flora, based on current knowledge of vegetation communities within an area. (e.g. South-east Queensland (Environmental Protection Agency, 2007; Watson, 2001), New South Wales (Bradstock and Kenny, 2003; Kenny et al., 2004), Victoria (DSE, 2004, 2008; McCarthy, 2000; Tolhurst, 2000; Wouters et al., 2000), Northern Territory (Edwards and Russell-Smith, 2008), South Australia

(DEH, 2006a, 2007; Dowie, 2005; Wouters, 2006), Western Australia (Burrows, 2008; CALM, 2005b, 2006; Department for Planning and Infrastructure, 2005a, b)). But the knowledge of the fire ecology on resident animal species is often currently insufficient to formulate comprehensive fire regime thresholds for the management of fauna species (Clarke, 2008; Kenny et al., 2004; Tasker et al., 2006), although an interim guideline based on active adaptive management principles has been developed to assist managers to make expeditious decisions about fire management practices for protecting and managing quokka populations and habitat while meeting other fire management objectives (Burrows et al., 2006b).

These guidelines can be used in the formulation of fire management plans by private land owners and land managers. While individual property owners may not always consider biodiversity conservation as part of their fire management, the community at large have started to incorporate conservation of biodiversity into regional land management goals, particularly in the last decade (Gill et al., 2002a; Morton et al., 1995). To date, ecological prescribed burning in the arid and semi-arid regions has mainly been confined to those National Parks and Reserves where research has significantly advanced our knowledge of the fire dynamics for the area. In central Australia, the Commonwealth Government is responsible for the management of Uluru - Kata Tjuta National Park (Uluru-Kata Tjuta Board of Management and Parks Australia, 2000). Here, for example, a patch burning strategy is used, based on traditional patterns of burning. The traditional Anunga owners and Parks Australia work together to determine which areas should be burnt each year. This combines traditional ecological knowledge with the use of GIS, and the results of ecological studies by western scientists.

There is a need for more landscape scale, medium to long term, replicated experiments around the country, which can examine the interactions between “fire regime, ecological function and an extensive range of biodiversity” (Williams et al., 2003b). It could be potentially dangerous to include the manipulation of fire regimes for maintaining the health of our ecosystems on a landscape scale into management plans, when so little is known of the potential outcomes.

2.5.4 Holistic Adaptive Management

While we recognise that our understanding of fire in Australian landscapes remains inadequate we must, nevertheless, act immediately in an effort to preserve biodiversity. As principle 15 of the (United Nations, 1992) states:

> *In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*

The 'ecologically appropriate' fire regime approach, set in an ‘adaptive management’ framework, has been advocated as a sound basis for ecological fire research and management across Australia for a number of years (Benson, 2001; Ellis et al., 2004; Keith et al., 2002; Williams et al., 2003b; Woinarski and Fisher, 2003). Adaptive management has been defined in various ways since its development in the early 1970s. The definition most often used in Australian fire management is that of the British Columbia Ministry of Forests and Range (2008) :

> *Adaptive management is a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form–"active" adaptive management–employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed.*

Adaptive management aims to minimise the risks associated with environmental management, given our incomplete knowledge and understanding of ecosystems. It starts with risk assessment, and setting explicit goals. Specific plans are designed and drawn up, based on the best available information for operational plans, or on the hypothesis being tested for research. These plans are implemented and the outcomes are monitored, documented and evaluated against predefined performance indicators. This may reveal critical knowledge that is currently lacking. The results are reported, and management guidelines, policies and practices are refined and updated, according to the lessons learnt from the process. Identified knowledge gaps are researched further (Andersen, 1991a; BC Ministry of Forests and Range, 2008; Keith et al., 2002).

It has also been recognised that a ‘holistic’ approach to land management is the key to a sustainable future. Morton et al. (1995) talked about the concept of stewardship, in which conservation and production are integrated, and management is not partitioned off into categories such as pastoral, Aboriginal, conservation, mining or tourism. Benson (2001) too called for adaptive management regimes that strike a balance between agricultural production and biodiversity conservation. We must also recognise the knowledge and resources available in Aboriginal communities (Andersen, 1991a; Aslin and Bennett, 2005; Burgess et al., 2005; Gill et al., 2002a). There is a strong community-based movement in the tropical savannas towards more active land management, facilitated by the Northern Land Council's Caring for Country Unit. Indigenous community-based natural resource management such as this can generate conservation benefit, along with opportunities for sustainable and culturally apt regional employment, applied education and economic development. Engagement in caring for ancestral lands can also have a positive influence on health and self-esteem and reinvigorate societal/cultural constructs, increasing collective esteem and social cohesion (Altman and Whitehead, 2003; Johnston et al., 2007b; Storrs et al., 2002). Woinarski and Fisher (2003) saw the need for better coordination of management across rangeland jurisdictions and land tenures, with clear goals, targets and responsibilities set at continental, jurisdiction, regional and property scales. Gill (2002a) also highlighted the need to develop a nationally coordinated programme of research into fire regimes, biodiversity and management systems across Australia's diverse climates, land uses and tenures.

Until very recently, this approach has mainly been theoretical, with two serious impediments to its national uptake: current lack of resources and of societal agreement (Woinarski and Fisher, 2003). As is often the case, it has taken what is considered a national disaster (the 2002-2003 bushfire season) to change our way of operating.

2.6 Current Legislation, Policies and Plans in Mainland Australia

Tasmania is excluded from this discussion as there are no arid or semi-arid areas in the state.

Inquiries into significant bushfires, such as the Black Friday bushfires in Victorian in 1939, the Ash Wednesday fires of 1983 through Victoria and South Australia, and the 1993-94 Sydney bushfires, have all led to changes in legislation, policies and practice. The inquiries prompted by the 2002–03 fire season in Canberra, NSW and Victoria, have been no exception (Auditor General Victoria, 2003; Ellis et al., 2004; Esplin et al., 2003; Mcleod, 2003). While many of the recommendations which came out of these inquiries were not new, they were given a coherent voice in these reports, and extra government funding to implement them.

These recommendations included:

- improved governance and coordination of policy development
- decision-making within a risk management framework, based on the Australian Standard for Risk Management, and using an adaptive management approach
- a zoning approach to the classification of fuel management areas, applied at the landscape scale, with all land managers and the community involved
- accelerated research to produce “burning guides”
- continued work in partnership with Indigenous Australians
- more pervasive and effective community education
- the establishment of a national network of long-term ecological research sites
- ongoing research

(Ellis et al., 2004; Kanowski et al., 2005).

Most of these recommendations are now being implemented by federal, state and local governments and fire agencies throughout the country, to one degree or another, or are currently under review (COAG, 2005).

Table 2.1 Examples of state legislation addressing fire in mainland Australia

State / Territoty	Legislation
New South Wales	Rural Fires Act 1997 Rural Fire Regulation 2008 Environmental Planning and Assessment Act 1979 Fire Brigades Act 1989 State Emergency Service Act 1989 State Emergency and Rescue Management Act 1989 Protection of the Environment Administration Act 1991
Victoria	Country Fire Authority Act 1958 Metropolitan Fire Brigades Act 1958 Emergency Management Act 1986 Forests Act 1958
Queensland	Fire and Rescue Service Act 1990 Integrated Planning Act 1997 - State Planning Policy 1/03 Disaster Management Act 2003
South Australia	Fire and Emergency Services Act 2005 National Parks and Wildlife Act 1972 Wilderness Protection Act 1992
Northern Territory	Bushfires Act 2004
Western Australia	Fire and Emergency Services Authority Act 1998 Fire Brigades Act 1942 Bush Fires Act 1954 Conservation and Land Management Act 1984 Emergency Management Act 2005

While each state has its own separate fire legislation and regulations (table 2.1), they must also all comply with sections of other federal environmental legislation such as the National Parks and Wildlife Act 1974, the Native Vegetation Act 2003, and the Environment Protection and Biodiversity Conservation Act 1999, as well as the Native Title Act 1993 and the Building Code of Australia 2008. Fire legislation must also be compliant with each state or territory’s environmental, native title, local government and building legislation, codes and policies. A fundamental principal of all these acts is that the responsibility to prevent and control bushfires rests with the individual landholders (owners and managers), be they public or private.

Fire services in Australia consist of both land management agencies, (such as Parks and Wildlife, and Forestry), and response agencies, (both metropolitan and rural fire brigades). In each state there is an authority charged with issuing burning permits, providing advice to the public and with undertaking prescribed burning, usually aimed at reducing subsequent wildfires. Policies and plans are developed by a range of organisations in the various states, but most commonly, for individual local government areas (councils/shires), and individual parks or reserves. There are also some regional plans and policies. State emergency plans also relate to bushfires, while fire management is usually part of Natural Resource Management Plans too.

Examination by the author of the major fire policies and plans being developed in each state, shows that many have changed since they were reviewed as part of the State of Environment Report in 2001 (CSIRO, 2001a). Most of the fire management systems now include a system for planning, monitoring and reviewing, and reporting, as well as operational guidelines. Plans normally cover both operational preparedness and emergency response. A brief overview of the major fire policies and plans being developed in each mainland state is given below, with an emphasis on the rural as opposed to metropolitan areas.

2.6.1 New South Wales

Following the devastating January 1994 fire emergency in NSW, bush fire risk management planning became compulsory in NSW under the Rural Fires Act 1997. This new act reflected a shift from fuel management to risk management in the prevention, mitigation, control and management of bush fires. NSW was cited as ‘an example of good practice’ in the COAG National Inquiry on Bushfire Mitigation and Management (Ellis et al., 2004). Improvements have continued, and it is now the state with the most developed policies and plans.

The objectives of the act are to provide:

- for the prevention, mitigation and suppression of bush and other fires in local government areas (or parts of areas) and other parts of the State constituted as rural fire districts
- for the co-ordination of bush fire fighting and bush fire prevention throughout the State
- for the protection of persons from injury or death, and property from damage, arising from fires
- for the protection of the environment by requiring to be carried out having regard to the principles of ecologically sustainable development.

The bushfire risk management planning process has recently been reviewed and an adaptive management process, compliant with Standards Australia (2004) Risk Management, AS/NZS 4360:2004 has begun to be implemented, which enables planning to be carried out in a standard way across the state (BFCC, 2008b). This process uses a more sophisticated risk analysis methodology than previously, comprising of five major steps: establishing the context, identifying risks, analysing risks, evaluating risks and treating risks. It now allows risk treatments to be prioritised and registered in a systematic way using a system of Bushfire Management Zones (table 2.2). The new Risk Management process is underpinned by three main requirements - communication and participation, monitoring and reviewing, and documentation (BFCC, 2008b; Tan et al., 2006). New and revised plans will use the new planning framework, with the knowledge and opinions of local people being given far greater priority than in the past. Performance indicators to the risk treatment strategies will be included to facilitate monitoring and reviewing, with documentation of results being essential.

Table 2.2 Bushfire Management Zones, NSW

Source: BFCC (2008b) and DECC (2007)

Zone	Description
Asset Protection Zone	Areas located around buildings, property or other assets, where fuel is managed to reduce the bush fire hazard to an acceptable level. This provides protection for life and property and highly valued public assets and values
Strategic Fire Advantage Zone	Areas where fuel is reduced to complement Asset Protection Zones, or in areas of high ignition potential (eg along roads, rail lines, power lines). SFAZs are located within large continuous areas to reduce the speed and intensity of bush fires, reduce the potential for spot fire development, and provide advantageous areas for safer fire suppression.
Land Management Zone	Areas more removed from the urban interface, where Asset Protection or Strategic Fire Advantage Zones are not appropriate. Fire management carried out in these areas is designed for both fire management and land management objectives (eg- ecological burns, post log burns, silvicultural burns). This includes reducing fuel levels in more remote areas of National Parks, State Forests or on agricultural holdings.
Fire Exclusion Zone	Areas such as rainforest, fire intolerant vegetation communities, fire sensitive cultural/historic heritage sites, pine plantations, or commercial crops, where it is appropriate to exclude fire completely. It is only in extreme cases that hazard reduction work is carried out in these areas.

In New South Wales, ministerial responsibility for bushfire response now lies with the Minister for Emergency Services, to whom both the New South Wales Rural Fire Service (RFS) and the New South Wales Fire Brigades report. The RFS is comprised of over 2,000 brigades and almost 70,000 volunteer firefighters, along with about 600 permanent staff at headquarters and regional offices.

Under the act, the Bush Fire Coordinating Committee is responsible for developing comprehensive policies, procedures and guidelines for the entire state, but does not have an operational role (BFCC, 2008a). It is comprised of representatives from a broad cross-section of organisations including the four fire fighting authorities in the State (NSW Rural Fire Service, NSW Fire Brigades, National Parks and Wildlife Service, and State Forests), local government, conservation interests, rural interests, the police, and community services.

The state is divided into 143 Rural Fire Districts, generally following local government boundaries, with a Fire Control Officer employed by each local council. Each has a district Bush Fire Management Committee, comprised of the various fire fighting authorities, land management agencies and community interests in the area (BFCC, 2006, 2008b). These committees prepare, review, monitor and revise plans to coordinate management of bushfires in their area. They attempt to coordinate planning across different land tenures (forests, farms, parks and private property) for protection of life, property, natural and cultural heritage, while taking into account the ecological requirements of threatened species and biological communities.

Each district Bush Fire Management Committee must develop a detailed Bush Fire Risk Management Plan which is reviewed every 5 years, and an annual Plan of Operations for areas defined and mapped as “bush fire prone”. The draft plans are subject to a public review process and approval by the Coordinating Committee prior to being adopted. These detailed documents map and describe the level of bush fire risk across all private and public land in the area, identify assets at risk (including life, property and natural and cultural heritage), and establish treatment options for these assets and areas. The role of fuel management is still an important element of the risk management approach, and a system of Bushfire Management Zones is used to manage them (table 2.2). At the operational level, depending on the level of risk and type of hazard identified, activities can include hazard reduction work, community education programs (such as the RFS FireWise, Rural FireWise and Bush FireWise programs (RFS, 2008), or the Nature Conservation Council’s Hotspots project (Conroy et al., 2006)), or specialised training and equipment for firefighting authorities). The Plan of Operations also covers resourcing, communications and actions to be followed in the event of an emergency.

Under the Rural Fires Act, 1997, all landholders (private or public) are legally required to prepare their own properties adequately and effectively to cope with bushfire, while ensuring that all activities are conducted with regard to the principles of ecologically sustainable development. Public and private landowners and managers of the land on which bush fire risk is situated, are required to implement the bush fire management plans. The Bush Fire Management Committees monitor the results, and report annually on the performance and success of the plan’s implementation to the Coordinating Committee.

Hazard reduction is commonly performed by burning, but can also be achieved by other methods such as mowing, slashing or hand clearing. The RFS will often facilitate these burns at the request of the landowner or manager. During the Bushfire Danger Period (usually October to March) a permit to burn may be required, but with no fires allowed during Total Fire Ban days. In 2002, legislative changes were made via the Rural Fires and Environmental Assessment Legislation Amendment Bill 2002 to amend the Rural Fires Act 1997 and the Environmental Planning and Assessment Act 1979. These included giving the Rural Fire Service Commissioner the authority to order all owners and managers of private, commercial and government land to conduct essential hazard reductions, compulsory auditing of the implementation of Bush Fire Risk Management Plans, and the implementation of Bush Fire Hazard Reduction Certificates.

A Bush Fire Hazard Reduction Certificate is an environmental approval, which may specify conditions that must be adhered to, when hazard reduction work is likely to impact on environmental concerns. The Bush Fire Environmental Assessment Code was introduced in 2003 to provide an environmental assessment process for authorities when determining applications for a certificate (Brompton et al., 2006). Since then, a certificate has been required in the urban interface if hazard reduction works are carried out on land where a Bush Fire Risk Management Plan applies (i.e. in a declared “bush fire prone” area). Revision of the Bush Fire Environmental Assessment

Code in February 2006 has expanded this to rural areas also. Certificates are not required for routine agricultural activities however. The Bush Fire Environmental Assessment Code includes standards for the protection of Aboriginal or other cultural heritage, and for prevention of air or water pollution, or soil erosion. The Threatened Species Hazard Reduction List, which was developed in consultation with the Department of Environment and Conservation, is a component of this code. It provides ecological guidelines for applying appropriate fire regimes (particularly fire interval thresholds) for plants, animals and endangered ecological communities, when using prescribed burning (Kenny et al., 2004). It also considers the potential impacts of mechanical hazard reduction works. Once a Bush Fire Hazard Reduction Certificate has been issued, no further environmental approval is required under NSW legislation.

The scope of Bush Fire Management Committee plans extends to the NSW National Parks and Wildlife Service's (NPWS) fire management. NPWS, which is part of the Department of Environment and Climate Change, is responsible for fire management of over 200 individual National Parks (about 15 of them within the arid or semi-arid zone) and many more nature reserves, covering about 8% of the land area in the state. In the Rural Fires Act 1997, the Service is defined as both a 'firefighting authority' and a 'public authority'. As a member of the Bush Fire Coordinating Committee they help formulate and review state policy and strategies (DECC, 2007). They also develop their own internal fire management polices which are integrated and consistent with these, and other NPWS and inter-agency policy positions (DECC, 2008).

The NPWS have embraced the adaptive risk management approach throughout all their operations, that specifically addresses biodiversity conservation, for a number of years (NPWS, 2002). They have recently completed a review of fire management on their lands, and their new strategic fire management policies and procedures, which adopt the Australian Standard on Risk Management (AS/NZS 4360: 2004), are published in the NPWS Fire Management Manual (2007). These follow the standard emergency management risk framework 'PPRR' (Prevention of unplanned fire; Preparedness measures to ensure an appropriate response to fire; Response procedures to control fire in a safe and efficient manner; and Recovery programs to mitigate the undesirable impacts of fire and fire suppression activities).

The primary objectives of fire management are to:

- protect life, property and community assets from the adverse impacts of fire;
- develop and implement cooperative and coordinated fire management arrangements with other fire authorities, reserve neighbours and the community;
- manage fire regimes within reserves to maintain and enhance biodiversity;
- protect Aboriginal sites and places, historic places and culturally significant features known to exist within NSW from damage by fire; and

- assist other fire agencies, land management authorities and landholders in developing fire management practices to conserve biodiversity and cultural heritage across the landscape.

Five year Fire Management Strategies (replacing the old Fire Management Plans) are being produced for either individual, or groups of, Parks and Reserves, which are then used as the basis for preparing annual Operational Fire Plans. These plans use Bush Fire Management Zones (table 2.2) to apply specific management strategies. The Bush Fire Environmental Assessment Code is used as the basis for environmental impact assessment for carrying out bush fire hazard reduction work. In areas where the fire risk is low and the issues are less complex, the fire management strategy will be prepared as a supplement to other management plans. Other parks have more complex fire issues, requiring a separate fire management strategy to be prepared. These new Fire Management Strategies are currently being rolled out, as old plans are due for revision and more parks and reserves have new strategies developed (DECC, 2008). The NPWS Plans/Strategies are also incorporated into the relevant Bush Fire Management Committee plans.

2.6.2 Victoria

The Country Fire Authority (CFA) was constituted under the Country Fire Authority Act 1958. There are 9 CFA Areas and 20 Regions, covered by over 1200 CFA brigades who respond to a variety of fire and emergency incidents.

Beginning with the formation of its Risk Management Department in 1994, CFA progressively introduced risk management principles into its business. In 1997 amendments to the CFA Act 1958 required each municipality to prepare and maintain a Municipal Fire Prevention Plan (MFPP). To support the amendments, CFA produced the Municipal Fire Prevention Planning Guidelines (1997) to assist municipalities with the planning process. These Guidelines introduced risk management, and also emphasised the need to consider all fire-related events, and to be inclusive of the community and other stakeholders. The 2001 CFA audit of MFPPs identified that 16 out of 63 municipalities had not successfully implemented the risk management methodology or adopted the planning approach outlined in the Guidelines. Evidence from the CFA Best Practice Review of Municipal Fire Prevention, carried out at the same time, revealed that many municipalities found the Guidelines too difficult to implement (Walker, 2001).

As identified by the CFA's Review (Walker, 2001), the Inquiry into the 2002–2003 Victorian Bushfires (Esplin et al., 2003), and the 2003 Auditor General's Performance Audit of Fire Prevention and Preparedness (Auditor General Victoria, 2003), problems associated with the MFPPs included:

- Lack of integration across land tenure
- Agency specific planning and a lack of stakeholder participation
- Lack of 'ownership' of the planning process at the municipal level

- Implementation failure
- Legislative complexities
- Links to Emergency Management

(IMFMP, 2005)

Funded by the Victorian Government, the Integrated (Municipal) Fire Management Planning (IFMP) project was established in 2004 to implement a number of the recommendations from these reviews. The Country Fire Authority (CFA) is coordinating the project as the lead state agency.

Following extensive consultation with agencies, organisations and the community, the Integrated Fire Management Planning Framework for Victoria has recently been developed (CFA, 2007). This framework provides a mechanism for a new holistic strategic approach, focusing on a move from fire prevention to fire management, planning for all fire risk environments and the use of fire for cultural and ecological purpose. Critical to IFMP is the 3 tiered planning approach with a State, 8 Regional and 85 Municipal level planning units. Supported by risk analysis approaches and a dedicated independent fire planning support team, each level will have responsibility to deliver the service most appropriate to it.

The State Fire Management Planning Committee is currently developing a Strategic Plan for fire management which aims to address the need to develop integration within and across agencies in the state. It will create long term and strategic direction; policy, principle and high level process; and overarching frameworks and peak body structures for integrated regional/divisional and community based planning for fire management in the state of Victoria. A multi-agency team will develop a “Consistent Risk Assessment Process”.

Planning for the implementation of IFMP at both regional and municipal level integrated fire planning is now underway. The Regional committees will undertake the strategic analysis and plan for their region, while at the municipal and local level treatments will be delivered in a cooperative way that services local communities. IFMP will gradually be introduced across the state over the coming years.

One of the key agencies in IFMP is the Department of Sustainability and Environment (DSE), who is responsible for fire management on public land in Victoria (roughly one third of the state). The Code of Practice for Fire Management on Public Land ('the Code') was first developed in 1995 to provide the strategic framework for the efficient, effective and integrated management of fire and fire related activities on public land in Victoria. The Code was divided into three sections: broad principles; protection from wildfire; and a framework for the planned use of fire ‘to achieve land management objectives’ and was recognised as good practice (Auditor General Victoria, 2003; Ellis et al., 2004). Following its compulsory ten year review, community education and engagement, and monitoring and reporting were areas identified in need of improvement. The Code has been revised to operate under a number of principles: general, risk management (consistent with the Australian standard on Risk Management), prescribed burning (operations), fire protection, environmental management, and community partnership principals (DSE, 2006). Each of the five DSE fire regions will develop regional instructions/guidelines/prescriptions. Each DSE fire district in Victoria already has a Fire Protection Plan, which applies for up to 10 years. These Fire Protection Plans will gradually be replaced by new Fire Management Plans as outlined in the new code, using a system of Fire Management Zones. Each year, DSE also prepares Fire Operations Plans for public land in Victoria, which provide a guide to the fire prevention and preparedness works to be carried out within each Fire District in a three-year forward looking program. Key to the new code is the ongoing process of monitoring and reviewing, with documentation of results.

An Overall Fuel Hazard Guide has been developed for Victoria (McCarthy et al., 1998). DSE have also produced a document outlining the principles, standards and planning procedures for ecological burning on public land throughout Victoria (DSE, 2004). The guidelines have been trialled in a number case studies in different environments; sandplain heathlands in the mallee, Wyperfeld National Park, (Wouters et al., 2000); damp forests at Mt Cole, Western Highlands (Tolhurst, 2000); and lowland forest and heathland at Yeerung, East Gippsland (McCarthy, 2000). Ongoing fire and biodiversity research addressed through DFES has three components (DSE, 2008):

- A case study in south-western Victoria (the Casterton Fire and Biodiversity Project), assessing the management implications of alternative bushfire regimes on fauna in heathy stringybark woodlands
- A review, and expert consideration of the scientific literature, defining ecosystem outcomes and resilience ‘states’ from initial landscape fire regimes; and
- Provision of expert knowledge (e.g. through training courses, technical committees and workshops, and in response to specific requests).

2.6.3 Queensland

Under the Fire and Rescue Services Act 1990, responsibility for fuel management is on the landowner. The Rural Fire Service, an operational division of the Queensland Fire and Rescue Service, is responsible for administering and supporting the network of over 1,500 fire brigades with approximately 44,000 volunteers that protect 93% of the state of Queensland (DES, 2008b). It convenes the interdepartmental Bushfire Management Coordinating Committee, which has stakeholder representation across Government.

The Risk Management Unit of the Rural Fire Service is responsible for developing and supporting a community-based approach to fire management in rural and rural/urban interface “iZone” areas throughout the state. They have adopted the Australian and New Zealand Standard for Risk Management (AS/NZS 4360:1995). The unit produces Bushfire Risk Analysis maps for each local government area (DES, 2008a). This information is then used to determine the best way of managing that risk.

Some individual councils and community groups have produced Bushfire Management Strategies and Plans, although the focus is often on hazard management rather than ecological management, and the effort has mostly been confined to the populous southeast section of the state (e.g. (Gold Coast City Council, 1998; Landmarc Ltd., 2003)). People in rural residential and park residential areas are also encouraged to develop individual property fire management plans, and register them with Council and the local rural fire brigade. The South East Queensland Fire and Biodiversity Consortium, have developed a suite of materials including the 'Individual Property Fire Management Planning Kit' (FABC, 2002), as well as Ecological Guidelines (Environmental Protection Agency, 2007; Watson, 2001), and Operational and Strategic Fire Management Manuals (Tran, 2002; Tran and Peacock, 2002) aimed at landowners and local government authorities in their preparation of plans and strategies. The consortium, which was formed in 1998, has members from a range of local government authorities and State government agencies, industry and the community.

The most significant change in recent policy is the introduction of the State Planning Policy (SPP 1/03): Mitigating the adverse impacts of flood, bushfire and landslide (DLGP/DES, 2003b) and it’s associated Guideline (DLGP/DES, 2003a). In either a high or medium severity bushfire hazard areas, (assessed using the Bushfire Risk Analysis maps produced by the Rural Fire Service), the SPP requires the preparation of a Bushfire Management Plan under certain circumstances. However, this does not apply to the arid and semi-arid regions, as these are all considered low bushfire risk areas.

The Queensland Parks and Wildlife Service is responsible for approximately 12 million hectares of land, about half of which is in remote low-impact locations. They drafted their adaptive Fire Management System in 2000, which has been adopted statewide (Melzer and Clarke, 2003). It includes a number of components. Fire planning involves developing a Fire Strategy, a Planned Burn Programme, and a Wildfire Response Procedure for individual areas. Up to seven management zones are identified – Protection, Wildfire Mitigation, Conservation, Sustainable Production, Rehabilitation, Reference and Exclusion. The Fire Strategies are approved by a Fire Referral Group comprised of representatives from relevant groups and individuals. The plans vary in complexity and may also be prepared as multitenure / multiagency fire management plans, or in association with a community bushfire protection plan. Stakeholder consultation and native title notification are also integral to the development of a Fire Strategy. Fire reporting and recording involves the monitoring of active fires, the reporting of the results of planned burns or wildfires, and the maintenance of fire history. As it is a relatively new system, the standard of fire management implementation varies across the State, but improvements to the system will continue (Leeson, 2006).

A set of ecological fire management guidelines have been developed for regional ecosystems, designed to enhance biodiversity (Environmental Protection Agency, 2007; Watson, 2001). These are derived from the best available scientific literature and relevant professional experts for each bioregion, but further research and monitoring is required.

2.6.4 South Australia

The Country Fires Act 1989 established the Country Fire Service (CFS), the Bushfire Prevention Advisory Council, and provision for Regional and District Bushfire Prevention Committees. But while this act stated that "proper land management principles" should be taken into account, there were no direct references to ecological sustainability, and no explicit criteria for the approval of burning. The 2001 State of Environment Report stated that there was "no formal process for fire management in South Australia" (CSIRO, 2001a). The emphasis was very much on prevention through fuel management, rather than the strategic and integrated approach to management.

As a result of the Canberra bushfires, a Bushfire Summit was convened by the South Australian Government in 2003, to examine bushfire prevention and suppression capacities in the state. Following on from that, the South Australian Fire and Emergency Services Commission, comprising the Country Fire Service, the Metropolitan Fire Service and the State Emergency Service, was established under the Fire and Emergency Services Commission Act 2005 (replacing the Country Fires Act 1989, the South Australian Metropolitan Fire Service Act 1936, and the State Emergency Service Act 1987).

The state is divided into six CFS regions, each with a regional management officer, and a Regional Bushfire Prevention Committee which co-ordinates bushfire prevention activities in its region and reports on them annually. The regions are further divided into 15 CFS Fire Ban Districts, each incorporating one or more rural council areas.

Individual rural councils have the responsibility to constitute a District Bushfire Prevention Committee, comprised of a range of personnel including the council(s) fire prevention officer(s), representatives from each of the local CFS brigades, as well as representatives of the National Parks and Wildlife Service, Forestry SA, other relevant organisations or agencies, and the community, as deemed necessary. These committees must formulate guidelines for the issue of permits within their area, help develop a Bushfire Prevention Plan for the upcoming fire season, and deliver annual reports on the bushfire prevention activities undertaken in their area and the outcomes. Generally, these activities include community education programs (such as Bushfire

Blitz meetings and the “Stay and Defend or Go Early” policy), an annual inspection of all private and public lands, issuing of notices to properties posing a fire threat, and fuel hazard reduction work where necessary. During the declared Fire Danger Season, the use of fire is controlled through a permit system, administered through the Fire Prevention Officer or other authorised officers in the rural councils. Prescribed burns on private lands are usually conducted by the CFS, either as a result of a landholder request, or high fuel loads identified by the Bushfire Prevention Committees.

Under the new act, the CFS and the bushfire committees, in carrying out their duties to protect life, property and environmental assets from fire, must:

- have due regard to the impact of their actions on the environment and
- seek to achieve a proper balance between bushfire prevention and proper land management in the country

Environmental assessment of bush fire hazard reduction activities should now be undertaken prior to any bush fire hazard reduction work, to ensure that the natural values are protected. But there are no specific ecological guidelines on how to achieve this in any of the Bushfire Prevention Plans. Guidelines for the management of native roadside vegetation in relation to fuel hazard reduction burning have been developed by the Native Vegetation Council (NVC, 2006). The model used by many councils for their bushfire prevention plans was developed by the CFS in the late 80’s (e.g. Ceduna (DCC, 2004) and the Coorong (CDC, 2008)) and do not reflect current risk management methodologies, adaptive management and zoning approaches.

The vast majority of South Australia falls outside the standard council areas however, and is either part of the Outback Areas Community Development Trust, or one of a small number of remote Aboriginal communities. Here, permits are issued through the regional fire protection officer or a number of other authorised officers. For these out-of-council areas only one Bushfire Prevention Plan has been prepared to date - that for the Amata Community and Tjurma Homelands in the Anangu Pitjantjatjara lands in the far northwest of the state (Pers. Comm., Fire Prevention Officer, Region 4 - Flinders, Mid North and Pastoral Areas, CFS)

Following the Wangary, Eyre Peninsula Bushfire of January 2005, there has been the first formal review into bushfire prevention management in the state since the early 1980’s (MBMR Reference Group, 2007). The major causes to the challenges within the current system were identified as:

- Limited clarity (including definition of purpose and who does what, when and why?)
- Limited framework (standards, policies, guidelines, procedures and reporting)
- Limited capacity (competing levels of service, resource allocation)
- Limited capability (competencies in bushfire management)

The key outcomes of the review are summarised as follows:

- Planning based on risk management (consistent with AS/NZS 4360:2004)
- Bushfire Planning linked to Emergency Management Planning
- Two rather than three-tiered committee system
- Local community and Local Government involvement maintained
- Expanding Prevention, Preparedness, Response, Recovery (not just prevention)
- Accountability of the Chief Officer of SACFS
- Clear linkages between the committees
- Allows for community involvement
- Expanded the number of stakeholders
- Proposing a Code of Practice
- Proposing accredited self-regulation for some fire management activities
- Streamlining processes for prescribed burning
- Proposing incentives for “best in class” and “best practice”
- Agreed on a number of principles (individual and community resilience)

This represents a major paradigm shift from the emphasis on prevention alone, to a comprehensive approach to bushfire management through prevention, preparedness, response and recovery. The Review recommendations are predominately of a strategic or policy nature, many requiring amendments to the SA Fire and Emergency Services Act and Regulations 2005. CFS has commenced the implementation of the findings of the review.

The Department of Environment and Heritage (DEH) supports the Country Fire Service in minimising the risk associated with fire in natural bushland, as well as having direct responsibility for on-ground management of 331 reserves, covering over 20% of the state. In 2000 DEH had one fire management officer and a budget of about $300,000. Fire management in conservation reserves was still aimed at prevention, although little prescribed burning had been undertaken in the last decade (Richards, 2006), and there were no fire management plans aimed explicitly at enhancement and conservation of biodiversity (CSIRO, 2001a).

In 2003, with $10 million extra government funding, a dedicated DEH Fire Management Program was established. Since its inception, the branch has developed a comprehensive strategic fire management policy and planning framework, for the conservation of biodiversity, and to minimise a fire’s impact on life and property (DEH, 2005). Policy and procedures for risk assessment are consistent with the Australian and New Zealand Standard AS/NZS 4360 for Risk Management (Smith, 2006c), while a policy on fire management zoning designates areas into three zones: Asset Protection, Buffer and Conservation (Smith, 2006b). DEH has increased its operational capabilities in the event of a fire. Also, in conjunction with other Government agencies, DEH has significantly increased the prescribed burning program throughout the state (operating under the Code of Practice for Prescribed Burning (GALFC, 2004)), and developed guidelines for the construction and maintenance of firebreaks and fire tracks (GAFLC, 2005) and a fuel hazard guide (DEH, 2006b).

New fire management plans in DEH reserves are based on an adaptive management approach, incorporating ecological fire management supported by contemporary research (Smith, 2006a; Wouters, 2006). Ecological guidelines for South Australia are currently being developed (DEH, 2006a, 2007; Dowie, 2005; Wouters, 2006). In the meantime, fire management plans will set guidelines for conservation zones based on the best available fauna information and expert opinion. The only plan adopted to date is that for Flinders Chase, Kangaroo Island. A number of other fire management plans will be adopted in the near future (parts of the Mount Lofty Ranges, Fleurieu Peninsula, Eyre Peninsula, and the Flinders Ranges, as well as the Nargkat district, Bookmark Biosphere Reserve and Billiatt Wilderness Protected Area in the semi-arid Mallee country in the southeast of the state) (DEH, 2008). No specific planning or research has been carried out in the arid interior of the state so far, although it is on the long-term agenda (Pers. comm., Mike Wouters).

Anangu Pitjantjatjara Lands (AP Lands) in the far northwest of the state cover almost 10% of the land area of South Australia. Since the early 1990s AP Land Management (who have responsibility for biodiversity and cultural land management) have been working with Nguraritja (traditional owners) to re-establish patch-burning activities, particularly focusing on protecting the larger and denser areas of mulga known to support malleefowl (Lang et al., 2003). Under the new Commonwealth Government ‘Caring for Country’ natural resource management initiative, (continuing on work initiated under the Natural Heritage Trust’s national ‘Landcare’ Program), a number of projects have been set up on Aboriginal lands (NRM, 2008). The AP Lands Fire Management Strategy project will utilise traditional ecological knowledge, current 'scientific' knowledge, anthropological expertise, and land systems data to develop a coherent and strategic plan for fire management. As part of this process workshops are held to bring senior traditional owners together with younger people, ecologists and Anangu Pitjantjatjara Land Management support officers (and sometimes pastoralists ecologists), to facilitate the inter-generational transfer of knowledge concerning patch burning, and to develop an appropriate fire management strategy for the AP Lands. Currently Amata (a community of just over 200 people, 115 km directly south of Uluru) is the only community that has had a Fire Management Plan drawn up but the fire vehicle is often out of fuel, the water tank empty, and there is a lack of training (Stein, 2008).

2.6.5 Northern Territory

The Bushfires Act 2004 now forms the legal framework for bushfire management in the Northern Territory. A fundamental principal of the act is that the responsibility "to prevent and control bushfires" rests with the individual landholders (owners and managers), be they public or private.

Bushfires NT, a section of the Department of Natural Resources, Environment and the Arts and Sport, is responsible for implementing the act (Bushfires NT, 2007). It is mainly responsible for coordinating fire prevention and management across most of the Territory, as opposed to fire fighting, but is also involved in research, policy making, education and training. They also support the 21 volunteer Bushfire Brigades (the majority in the tropical area around Darwin and Katherine). The Northern Territory Fire and Rescue service is primarily responsible for fires in the urban centres, with permanent fire stations in Alice Springs, Tennant Creek and Yulara, along with another 7 in the north. The Bushfires Council of the Northern Territory is a statutory body under the Bushfire Act, responsible for advising the Minister for Parks and Wildlife on bushfire prevention and control.

Bushfires NT operates under a series of policy guidelines to achieve its fire management objectives, which include:

- protection of life, property and the environment from the effects of wildfires
- maintenance of natural resources, including native ecosystems and productive lands, by the use of appropriate fire regimes

The high levels of risk, the lack of resources and the effort required to suppress wildfire, mean it is usually only suppressed when human life, assets or environmental values are threatened. One of the main objectives of Bushfires NT is "to reduce the total area burnt by wildfire in the Northern Territory". This is partly achieved through the issuing of permits to burn in either a permanent Fire Protection Zone (there are two in the desert region – a 50 km radius around both Tennant Creek and Alice Springs), or a temporarily declared Fire Danger Area, and through total fire bans during periods of very high or extreme fire danger. It is the responsibility of landholders to control fire on their property, and they are encouraged to have fire management plans in place to help prevent large and intense wildfires. Bushfires Council staff and volunteers work with landholders to plan and implement fuel reduction programs. Rural landholders, both public and private, can be forced to establish firebreaks and reduce fuel loads on their property if it poses a wildfire threat. In the rural areas of the Vernon (Darwin) and Katherine regions this is achieved through the annual Firebreak Enforcement Program. Aerial Prescribed Burning (APB), where a burnt sector is created early in the dry season by dropping incendiaries from an aeroplane or helicopter, has been used in the Northern Territory savannas since the early 1980s for wildfire mitigation (McGuffog et al., 2001; Price et al., 2007).

In the arid and semi-arid zones however, few pastoralists or other land managers plan or manage directly to prevent large wildfires, as the risk is relatively low in most years (Edwards et al., 2008). The Alice Springs Crown Land Strategic Fire Management Plan was released in 2004, following several large bushfires around the Alice Springs region in late 2002. It is primarily aimed at creating firebreaks around residential properties in the town boundary, and also includes a fire protection plan and action table, listing who is responsible for carrying out the works and the frequency of work. It is supported by a public awareness campaign on the importance of minimising fuel loads and the dangers of the indiscriminate lighting of fires.

The Parks and Wildlife Service (PWS) of the Northern Territory manage parks and reserves from the tropical north to the deserts of Central Australia. Many have management plans which identify fire as an issue for biodiversity, and have specific Fire Management Strategies and annual Fire Action Plans, although without specific guidelines for appropriate regimes for long-term conservation (NRETAS, 2008; Williams et al., 2001). Fire management planning is undertaken annually, but lack of ranger experience (due in large to high staff turnover rates), time, budget levels, access, and expert support often limits the quality and efficiency of planning, record keeping and reporting, as well as implementation (Edwards et al., 2008). There is also still a lack of lack of long-term holistic strategies for the major parks , with the exception of Uluru-Kata Tjuta and Kakadu National Parks, which fall under the responsibility of the Commonwealth Government (Director of National Parks, 2007; Uluru-Kata Tjuta Board of Management and Parks Australia, 2000).

Individual plans need to be set in the context of a broader regional strategy. The Northern Territory is divided into ten Fire Control Regions that reflect varying land use, population density, climate, soil and vegetation type, with a Bushfires Committee representing each region. At the time of the 2001 State of Environment Report, fire management plans written for each region, were focused primarily on operations for prevention and mitigation of wildfires, and specific guidelines outlining appropriate fire regimes for the long-term conservation of biodiversity were generally not provided (Williams et al., 2001).

A regionalised strategic Bushfire Management Strategy for the Northern Territory is currently being developed by Bushfires NT and the Bushfires Council, with extra funding provided through the Natural Heritage Trust (Myers et al., 2004). This project is undertaking a regionalised assessment of fire management priorities and impediments, and developing regional fire management guidelines for each of the 10 designated fire control regions. These will provide some specific guidelines for landholders on managing fire to maintain diversity of species and ecosystems. These guidelines will also recognise that traditional burning is still practiced on Aboriginal Land in the Northern Territory.

Since the mid 1990's a substantial research effort has addressed various aspects of ecology and fire management of the tropical savannas region (Russell-Smith et al., 2003d). The Tropical Savannas Cooperative Research Centre has been working on the project "Developing knowledge-based fire management for northern Australia savanna communities" with funding from The Natural Heritage Trust (NHT, 2008). This project provides a phased approach to coordinating identified key fire management issues across northern Australia.

The project involves three interlinked components to:

- develop, implement and monitor regionalised best practice fire management guidelines
- develop fire management capacity in three overlapping key sectoral areas (indigenous interests, pastoral management and biodiversity conservation)
- build a north Australia fire management knowledge forum

Ecological thresholds have been developed in the effort towards developing a sustainable, long-term fire management plan for western Arnham Land (Edwards and Russell-Smith, 2008).

Recently, a review of fire management on central Australian Conservation Reserves described broad fire management regimes, with associated implementation guidelines (Duguid et al., 2009).

Back in the 1990s, the Warlpiri people of the Tanami Desert expressed a desire that resources be directed to facilitating their ground travel, through the development of a network of graded vehicle tracks, rather than aerial burning (Nash, 1990). These would allow access by vehicle to country for a multitude of purposes, including burning, and on the same trip hunting and food-gathering, and renewing contact with sites and Dreamings; whereas aerial burning is a single-purpose trip, with minimal contact with country, and much control passed outside Warlpiri hands.

Aboriginal involvement in fire management is increasing through community ranger programs such as Caring for Country and Landcare (Altman and Whitehead, 2003; Storrs et al., 2002; Yibarbuk et al., 2001) and joint management on many PWS reserves (Director of National Parks, 2007; Edwards et al., 2008; Uluru-Kata Tjuta Board of Management and Parks Australia, 2000). In central Australia the Commonwealth Government is responsible for the management of Uluru - Kata Tjuta National Park. The traditional Anunga owners and Parks Australia work together to determine which areas should be burnt each year, using a patch burning strategy based on traditional patterns of burning.

But on many Aboriginal lands people's opportunity to visit remote country and burn are now greatly reduced; in larger communities especially, the knowledge is not being passed onto the younger generation; and major social conflicts can occur, within communities when the wrong people burn country, or with other stakeholders with different priorities (Edwards et al., 2008).

2.6.6 Western Australia

There is currently no single organisation or agency with overall responsibility of fire management and suppression in the state.

Under the Fire and Emergency Services Authority Act 1998, the Fire and Emergency Services Authority (FESA) of Western Australia was established in 1999, to improve planning and coordination across the State's emergency services. The Authority administers the Fire Brigades Act 1942 and the Bush Fires Act 1954. With almost 30,000 volunteer and career firefighters around the state, in over 600 brigades (bush and metropolitan), they are responsible for the prevention, control and extinguishment of fires, as well as other emergencies and hazards in the Gazetted Fire Districts (Perth, regional centres and some rural townships). The majority of brigades operate under the direction of the respective local government authority or Shire. FESA provides advice to Local Government and landholders on fire management planning issues, and is responsible for major wildfire incident management (SEMC, 2005).

Local Governments are responsible for their particular area, apart from Gazetted Fire Districts. Local government controls the use of fire through a permit system during the times of highest fire hazard (restricted and prohibited burning times). Permit burns can be carried out by anyone for a variety of purposes including agricultural clearing and hazard reduction. Local governments often use the Volunteer Bush Fire Brigades to carry out strategic fuel reduction in their local areas. They may also issue orders to property holders to create fire breaks or reduce fuels. Local governments are currently not required to consider possible biodiversity loss in native vegetation when considering applications for burn permits (Boulter, 2002).

The Department of Conservation and Land Management (CALM) was formed as a result of the Conservation and Land Management Act 1984. In July 2006 the Department of Environment and Conservation (DEC) was established, bringing together the Department of Environment and CALM. For the purposes of this document I will use the term DEC (CALM). DEC (CALM) has overall responsibility for the management of public lands (national parks, marine parks, conservation parks, regional parks, state forests and timber reserves, nature reserves, and marine nature reserves), which comprise about 9% of the state, and for the conservation of the state’s rich diversity of biota in general. In 2003 the Department was also allocated the role of managing fire preparedness on non-metropolitan, non-townsite Unallocated Crown Land, and Unmanaged Reserves, which cover a further 35% of the state. The responsibility for fire suppression on these lands remains with local government. DEC’s (CALM’s) fire management procedures are governed by some provisions of the Bush Fires Act 1954, but principally by the Department’s Fire Management Policy (Policy Statement No 19). The Department must also comply in general with the Wildlife Conservation Act 1950 and the Commonwealth Environment Protection and Biodiversity Conservation Act 1999. There are plans to replace the outdated and inadequate

Wildlife Conservation Act with a new Biodiversity Conservation Act in the near future. The state is divided in nine regions.

The WA Environmental Protection Agency (EPA) conducted a public review of CALM’s fire management in the southwest forests in 2004 (EPA, 2004). While the results were generally very favourable, they recommend that a greater emphasis be placed on biodiversity goals, using an adoptive management framework with performance indicators, and better monitoring and auditing. This resulted in Policy Statement No 19 being updated in 2005 to incorporate these recommendations (CALM, 2005a).

This revised Fire management Policy outlines overall departmental strategies on safety and risk, use of fire, fire suppression, wildfire prevention, liaison, and research. In prescribed burning plans, requirements for biodiversity conservation outcomes are given first consideration over objectives for strategic protection from wildfires. Three year indicative prescribed burning plans and annual burning plans are to be prepared in consultation with traditional owners, the community, government agencies and specific stakeholders. Yearly fire preparedness and response plans area also to be developed for each district. Written prescriptions must be prepared and approved before any prescribed burns are undertaken, and fires managed to reduce the risk of smoke. Outcomes are to be monitored and subject to periodic audit. Unplanned fires may be suppressed or left to burn depending on the risk to life, cultural and community assets and environmental values; the environmental impacts of suppression activity; and the feasibility of suppression. The Department will utilise the Australian and New Zealand Standard for Risk Management (AS/NZS 4360) as a basis for its approach to manage wildfire risk. The Department will form partnerships with other relevant agencies such as the Fire and Emergency Services Authority, local government authorities and the volunteer Bush Fire Brigades in carrying out its fire management role, and integrated fire management plans will be developed where appropriate. Public education on the role and effects of fire, and application of planned fire and fire suppression operations, is also vital. DEC (CALM) has adopted an adaptive experimental management framework in an effort to gain a greater understanding of the most appropriate fire regimes for the various regions. The Department will sponsor and undertake research into fire ecology and fire behaviour and ensure the resultant knowledge is disseminated to fire managers (CALM, 2005a).

In the fire-prone southwest forests, DEC (CALM) has developed and implemented fire management practices since the 1960’s, with the fuel hazard reduction programme (both aerial and on-ground) as a key strategy (EPA, 2004). Wildfire Threat Analysis is a decision support tool developed by DEC (CALM), originally for use in WA’s forests (Muller, 1993). It has been used by DEC (CALM), FESA and many, but not all, local governments to identify the likelihood of bushfire and its consequence on fire vulnerable values, in preparing fire management plans for towns, communities and DEC (CALM) estates throughout the southwest forest region (and to a more limited extent elsewhere in the state) (SEMC, 2005). Three separate management plans for the southwest forests were revoked by the new Forest Management Plan in 2004 (DEC, 2008a). Twenty six Landscape Conservation Units (areas within which plant species and communities have evolved under similar environmental conditions) have been identified, and an acceptable fire regime and idealised fire age distribution for each unit has been determined. This, along with the new *Fauna Distribution Information System* for southwest forest areas Christensen (unpubl.), allows biodiversity to be incorporated more effectively in analysis and planning in the southwest forests (EPA, 2006b). A range of evidence-based practical fire regimes have also recently been developed for the region (Burrows, 2008).

The WA EPA also conducted a review into the environmental impacts of the frequency of fire in the Kimberley and other rangeland regions in 2006 (EPA, 2006a). The EPA found the frequency, extent and intensity of fires to be of considerable concern, particularly in the northern Kimberly regions. It reported a widespread concern among all rangeland agencies, land managers and occupiers about the lack of resources for fire prevention and suppression, and also for fire planning on a regional and local scale. There is a considerable body of opinion that the current arrangement for fire management does not work, lacks clarity, is failing to protect biodiversity or the pastoral industry, and is confusing in regard to the roles and responsibilities for fire management outside of gazetted fire districts and DEC (CALM) Act managed land (EPA, 2006a, b). Some local government officers stated that their lack of knowledge of plants and animals, and the effect fires have on habitat, hampered planning efforts (EPA, 2006b).

This review of fire in the rangelands found that DEC (CALM) management practices are not as well developed here as in the southwest forests (EPA, 2006a). There is a perception that DEC (CALM) has failed to fulfill its own guidelines and that it has permitted fires to get out of control. DEC (CALM) recognises this, and is developing strategies to improve the situation, although it is concerned that current resources to achieve landscape scale change are inadequate.

In the Kimberly rangelands, which are dominated by savanna woodlands, most fire management is undertaken by FESA in conjunction with local government and pastoralists, and DEC (CALM) on their estates, through the Aerial Control Burning (ACB) program (Craig, 1999; EPA, 2006a). There have been a number of fire management projects in the Kimberley region in recent years aimed at strategic fire management, specifically the control of extensive and intense late dry season wildfires - the Kimberley Regional Fire Management Project (2000-07) (KRFMP Management Committee, 2004) and the EcoFire project. EcoFire is currently addressing the problem through regionally coordinated fire management, with Regional Burn Plans emphasising strategic early dry-season prescribed fires (AWC, 2008).

Elsewhere, in the more arid rangelands, while some fire management planning is occurring, it is patchy and fragmented, particularly outside CALM (DEC) managed areas. Unallocated Crown Land, is largely unmanaged, due to a lack of resources (EPA, 2006a).

A number of best practice fire management guidelines for property-scale management of pastoral leases, have been released by the Department of Planning and Infrastructure and the Pastoral Lands Board, for the Southern Shrubland and Pilbara (Department for Planning and Infrastructure, 2005b), and the Kimberly (Department for Planning and Infrastructure, 2005a). While not legally binding, they aim to assist pastoralists use and control fire on their properties to achieve production objectives in a sustainable and ecologically responsible way, suggesting appropriate fire regimes for different vegetation types and in different types of country. FESA is also working with pastoralists, the Pastoralists and Grazier's Association and the Indigenous Land Corporation to improve pastoral fire management. They acquired local grants to develop strategic pastoral station bush fire management in the Kimberley Region (2005-06), and the Pilbara (2006-07) (EPA, 2006b).

The only DEC (CALM) Regional Management Plans for rangeland regions were developed for the Goldfields Region in 1995 (CALM, 2004), and the South Coast Region in 1992 (CALM, 2002). Fire suppression in the Goldfields is difficult because of the constraints of remoteness, lack of access, communications and sparse population in suppression efforts. Fire management strategy has concentrated on conducting aerial and hand prescribed burns on Goldfields reserves to control wildfire. Aerial burning has also been carried out on an experimental basis in a few reserves to re-establishing environmental 'patchiness'. Rainfall, which might cause Goldfields vegetation to be at increased fire risk, is monitored, to enable preparations in advance.

In the South Coast region, there is more emphasis placed on having an effective fire detection system in place, along with an efficient radio communications network, and the means to suppress wildfires. There is also a more active program of prescribed burning for maintaining and promoting biological diversity.

More detailed Area Management Plans are available online for some individual parks and reserves (less than 10 of these areas fall within the arid and semi-arid zone) (DEC, 2008a). These plans are current for ten years, and all have a section which deals specifically with fire management, outlining the broad strategies that will be employed in the long term. The level of detail supplied varies greatly, in accordance with the level of background knowledge on the area (DEC, 2008a).

DEC (CALM) have recently developed Guiding Principles for fire management in the Kimberley savannas (CALM, 2006), and in spinifex dominated grasslands in the arid interior (CALM, 2005b). A plan developed by DEC (CALM) and FESA in an area of the Goldfields, across all land tenures, highlighted how the lack of ecological and fire behaviour knowledge about this area made it difficult to make informed planning decisions (EPA, 2006a).

DEC (CALM), FESA, and Western Power have partnered to develop a Bush Fire Threat Analysis across the whole of the state regardless of land tenure, based on the principles of AS/NZ 4360 (Risk Management) (EPA, 2006b). DEC (CALM) has also recently released its Code of Practice for Fire Management across the state (DEC, 2008b). It addresses the prescribed application of fire to department-managed lands; the management of wildfire on department-managed lands, including prevention of, preparation for, response to, and recovery from wildfire; and public participation, research, and monitoring.

The Kimberley Regional Fire Management Project (KRFMP) found that widespread landscape burning by Aboriginal people takes place in the northern Kimberley region, but not in the context of their traditional use of fire. Aboriginal people still practice customary burning in the Gibson Desert, while some indigenous controlled areas in the Goldfields region are burned frequently but not according to traditional methods (EPA, 2006b). Under the KRFMP, two Aboriginal Fire Control Teams were established to train people in both contemporary and traditional fire management. But these were disbanded when the project dissolved. Many communities undertake projects which are in effect ranger programs, but there is currently no co-ordinated Ranger program. The Kimberly Land Councils's Land and Sea Management Unit, in conjunction with a range of partners, has been active in developing a proposal to establish a sustainable Kimberley-wide Indigenous Ranger Program (DIA, 2006).

2.7 The Future

Management strategies must be continually refined by new information in an adaptive framework. Policies that integrate social and ecological needs across administrative boundaries and broad landscapes are required. At the same time, we must recognise that different landscapes have different fire regimes which require different fire management policies. As no single fire regime or spatial scale is suitable for all species, treatments must be tailored to specific sites if we wish to restore or maintain ecological integrity (Dellasala et al., 2004; Murphy et al., 2007; Russell-Smith, 2002). More research is required into these complex relationships in our pursuit to limit the most destructive aspects of fires, while preserving their social, economic and ecological benefits.

While empirical fire-biodiversity studies are immensely valuable, they are also expensive and very time-consuming. In the meantime, we can use the power of modern technology to help define our fire regimes and incorporate this quantified information into more complex computer models which can be used in various ways to better manage fire in our arid and semi-arid landscapes.

The use of geospatial information technologies will be an essential tool for developing, planning and implementing land management programs such as fuel modification and ecosystem restoration. They can facilitate the integration, manipulation, analysis and display of large complex sets of spatial data, and can aid in the visualization of wildland fire behaviour. They include remote sensing systems, geographic information systems (GIS), and specialized software for modeling and visualising locations and events (Perry, 1998). This information can be used in all stages of the fire management cycle, as described in figure 2.1 (General Accounting Office, 2003).

“Further research needs to more clearly determine the size and frequency of fires that best suit animals and plants with particular life history characteristics, but active fire management programs are required immediately. Remote sensing technology should be used to effectively monitor fire extent and pattern in the extensive spinifex-dominated landscapes and these data are needed to formulate fire management plans” (Allan and Southgate, 2002).

NOTE:
This figure is included on page 54 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 2.1 Wildland fire management activities

Source: General Accounting Office (2003)

Chapter 3

MAPPING, MONITORING AND MODELING

3.1 Remote Sensing Systems

Remote sensing systems collect data from one or more bands of the electromagnetic spectrum that are either emitted or reflected by the earth and the atmosphere. They include cameras, scanners, radar and sonar systems, radiometers, lasers, and thermal devices, which collect data from a distance - such as from a satellite or an aerial platform.

“Remote sensing plays an important role in obtaining quick and complete information on the occurrence and development of fires” (Li et al., 2001). Fire forms four signals that can be observed by this technology (Robinson, 1991):

- Direct radiation from active fires (heat and light)
- Smoke
- Post fire char
- Altered vegetation structure

There currently exist dozens of algorithms that use different satellite sensors to detect and monitor fire activity around the world (Lentile et al., 2006).

3.1.1 Hotspot Detection

Active fires can be detected by their thermal or mid-infrared signature during the day or night (figure 3.1), and by the visible light from the fires at night. The speed of obtaining and disseminating data on active fires is critical and requires sensors with daily overpasses. Hotspot detection algorithms are available for a number of systems (Ahern et al., 1999; Levine et al., 1999; Li et al., 2001) There follows a brief description of these, and references to research relating to them.

- The AVHRR (Advanced Very High Resolution Radiometer), aboard the NOAA (National Oceanic and Atmospheric Administration) polar orbiting satellites, give global coverage at a 1.1 km resolution with a swath width of 2,399 km and a revisit rate of 0.5 days. It has three bands in the visible-near infrared region and three thermal infrared channels. It is the most widely used sensor for long-term and large-scale fire monitoring, with data available back to the early 1990’s.
  (Craig et al., 2002; Flasse and Ceccato, 1996; Fraser et al., 2000a; Gautam et al., 2008a; Gautam et al., 2008b; Gong et al., 2006; Kaufman et al., 1990; Lasaponara et al., 1999; Pu et al., 2007; Robinson, 1991; Sukhinin et al., 2004; Yates and Russell-Smith, 2002)

NOTE:
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the thesis held in the University of Adelaide Library.

NOAA12 thermal 02 Dec 97 0836Z
Copyright 1997, CSIRO Division of Marine Research, Hobart

Figure 3.1 NOAA-AVHRR thermal image of 1997 NSW bushfires showing fire hotspots

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the thesis held in the University of Adelaide Library.

NOAA14 albedo 02 Dec 97 0455Z
Copyright 1997, CSIRO Division of Marine Research, Hobart

Figure 3.2 NOAA-AVHRR visible image of 1997 NSW bushfires showing burnt areas and smoke

- The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite has 32 bands which include special channels tailored to fire monitoring. It has a swath width of 2,330 km and a revisit rate of 1 to 2 days. With a resolution from 250 m to 1 km for different bands, it has allowed scientists to map fire across the entire Earth since 2000 with more detail and accuracy than ever before.
  (Chuvieco et al., 2008a; Giglio et al., 2003; Justice et al., 2002; Li et al., 2001; Miettinen et al., 2007; Potapov et al., 2008; Roy et al., 2008; Smith et al., 2007b; Vermote and Roy, 2002; Wang et al., 2007)

- The Defense Meteorological Satellite Program's (DMSP) Optical Linescan System (OLS) is a cloud imaging satellite with two broad spectral bands (visible - near infrared and thermal infrared) which can detect global night-time low light emissions such as fire and city lights. It has a fine spatial resolution of 560 m, a swath of 3,000 km and a revisit rate of 0.5 days. There is a digital archive going back to 1992.
  (Chand et al., 2007; Elvidge et al., 1996; Elvidge et al., 2001)

- The ESA (European Space Agency) ERS (European Remote Sensing Satellite) ATSR (Along-Track Scanning Radiometer) also has global coverage and produces infrared images with a 500 km swath width at a 1 km resolution. The ATSR-1 was launched in 1991, and the ATSR-2 in 1995 with additional visible channels for vegetation monitoring. It has a revisit rate of 3 days.
  (Arino and Rosaz, 1999; Bradley and Millington, 2006; Duncan et al., 2003; Eva and Lambin, 1998b; Kasischke et al., 2003; Spichtinger et al., 2004)

- The BIRD (Bi-spectral Infrared Detection) experimental small satellite mission (2001-2004), developed by the German Aerospace Centre (DLR), was the first mission dedicated to the task of active fire detection (along with active fire characterisation). It employed the new infrared higher spatial resolution sensor technologies of the Hot Spot Recognition System (HSRS) and the Wide-Angle Optoelectronic Stereo Scanner (WAOSS-B). It was launched in October 2001 and flew a 570 km circular sun-synchronous orbit with the local equator crossing time at 10:30 and 22:30 until early 2004. The HSRS has a swath width of 190 km and a 370 m resolution, while the WAOSS-B has a 533 km swath width and a 185 m resolution.
  (Briess et al., 2003; Siegert et al., 2004; Wooster et al., 2003; Zhukov et al., 2006)

- The GOES (Geostationary Operational Environmental Satellite) satellites orbit the equatorial plane of the Earth at a speed matching the Earth's rotation, in effect hovering continuously over one position on the surface. They orbit at a height which allows them a full-disc view of the Earth. The GOES I-M Imager is a five channel (one visible, four

infrared) imaging radiometer which sweeps to scan a full earth disc in 26 minutes or under. This offers continental coverage with high temporal frequency, but with a coarse spatial resolution (4 km or coarser) which allows close surveillance of fire development and smoke. They were first launched in 1975.
(Prins and Menzel, 1992; Robinson, 1991; Schroeder et al., 2008)

A review of active fire detection algorithms by Li et al. (2001) found that no single-sensor algorithm was optimal to be used in global operations, with some producing considerable commission and omission errors. Five fire detection algorithms (one developed for boreal ecosystems, the other four for global application) were tested on AVHRR data acquired over Canada during the 1995 fire season, again revealing large differences in performance (Ichoku et al., 2003). Both studies identified cloud cover, surface reflection, and threshold setting as issues that needed to be addressed.

3.1.2 Burned Area Mapping

Burned area mapping typically uses data from the near infrared and short-wave infrared bands, with red and near infrared bands being used occasionally (figure 3.2). The high contrast of burned areas and the good radiometric performance of recent sensors make it easier to produce robust and effective algorithms for burned area mapping than for active fire detection (Ahern et al., 1999). As with hotspot detection, burned area mapping algorithms have been developed for various sensors (Ahern et al., 1999; Levine et al., 1999; Li et al., 2004; Li et al., 2001).

There follows a brief description of some aspects of these sensors and references to research relating to them.

- NOAA-AVHRR
  (see details in section 3.1.1)
  (Arino and Melinotte, 1998; Craig et al., 2002; Fraser et al., 2000a; Kaufman et al., 1990; Li et al., 2000; Pu et al., 2007; Sukhinin et al., 2004; Yates and Russell-Smith, 2002)

- MODIS
  (see details in section 3.1.1)
  Near Infra Red channels centered near 1.24 and 2.13 m are sensitive to changes in the surface properties induced by the fire but are not obscured by smoke. Therefore, they allow remote sensing of burn scars in the presence of smoke.
  (Chuvieco et al., 2008b; George et al., 2006; Giglio et al., 2006; Justice et al., 2002; Li et al., 2004; Miettinen, 2007; Miettinen and Liew, 2008; Roy et al., 2008; Roy et al., 2002; Wooster and Zhang, 2004)

- ERS-ATSR
  (see details in section 3.1.1)
  (Eva and Lambin, 1998a, b; Korontzi et al., 2004; Simon et al., 2004; Smith et al., 2002; van der Werf et al., 2006)

- LANDSAT (Land Satellite) TM (Thematic Mapper) and ETM (Enhanced Thematic Mapper) provide much more detailed information on the spatial distribution of individual fires, but have a revisit rate of only once every 16 days. It has a 185 km swath and a spatial resolution of 15 to 120 meters.
  (Bowman et al., 2004; Eva and Lambin, 1998b; Hudak and Brockett, 2004; Kitchin et al., 1998; Roldan-Zamarron et al., 2006; Russell-Smith, 2002; Russell-Smith et al., 2002; Salvador et al., 2000; Smith et al., 2007a)

- The French system SPOT (Systeme Pour l'Observation de la Terre) VEGETATION sensor is also used for fine resolution mapping (2.5 to 20 metres) with a revisit rate of 1-4 days and a swath width of 60 km.
  (Bartalev et al., 2007; Chafer et al., 2004; Eva and Lambin, 1998b; Fraser et al., 2000b; Gerard et al., 2003; Korontzi et al., 2004; Silva et al., 2003; Stroppiana et al., 2002; Zhang et al., 2003)

- The SAR (Synthetic Aperture Radar) which is carried by the ERS (European Remote Sensing) Satellite, JERS (Japanese Earth Resources Satellite), and RADATRSAT (Canadian satellite) is a global microwave high-resolution system. In the weeks and months following a fire, the radar backscatter of the burned area becomes much more variable than that of the surrounding forest, enabling burned areas to be detected using multi-temporal SAR data.
  (Bourgeau-Chavez et al., 1997; Gimeno and San-Miguel-Ayanz, 2004; Gimeno et al., 2004; Levine et al., 1999; Siegert and Hoffmann, 2000)

- GOES
  (see details in section 3.1.1)
  (Zhang and Kondragunta, 2008)

A study in Indonesia described how eight different fire datasets were compared with each other and to fine spatial resolution burn scar maps. It used images from ERS-2 SAR, NOAA-AVHRR and DMSP-OLS. Each dataset detected different fires, with more than two-thirds of the fires detected by one dataset not being detected by any other dataset. None of the datasets detected fires in all test areas and they all had commission as well as omission errors. Fire regime, satellite sensor characteristics and fire detection algorithms all influenced which fires were detected (Stolle et al., 2004).

In a study in Borneo, Miettinen (2007) found that MODIS bands 1, 2 and 7 are the most sensitive bands in detecting burnt area in land-cover types dominated by green vegetation, while MODIS band 5 alone was best in land-cover types dominated by dry vegetation and soil. Miettinen and Liew (2008) compared 6 different methods of multitemporal compositing of MODIS images for detecting burnt area in Southeast Asian conditions. Results varied significantly between the various methods.

Studies such as these highlight how the available regional products are hard-coded to the specifics of a given ecosystem (e.g. boreal forest) and their mapping accuracy drops dramatically outside the intended area. In 2005 Roy et al. described an algorithm developed to map fire-affected areas at a global scale using MODIS surface reflectance time series data (Roy et al., 2005b). While recently, Loboda et al. (2007) presented a regionally adaptable semi-automated approach, based on Normalized Burned Ratio differencing (dNBR), to mapping burned area using a combination of active fire and burnt area MODIS data. It allows for easy modification of algorithm parameterisation to adapt it to the regional specifics of fire occurrence in the biome or region of interest.

3.1.3 Global Monitoring

Since 1972 data from satellites have been widely used to detect, map and monitor fires. Many of the early studies were individual projects run within states, provinces or forest management units. In 1998 the Committee on Earth Observation Satellites initiated a program of Global Observation of Forest Cover/Global Observations of Land Dynamics (GOFC/GOLD) as part of its Integrated Global Observing Strategy. Their goal is to create a consistent regional and global picture of the earth’s forests, and to monitor changes in the forests worldwide using satellite sensors (Ahern et al., 1999).

Several international programs have been established under the GOFC umbrella to map active fires globally. The International Geosphere Biosphere Program, Data and Information System’s (IGBP-DIS) Global Fire Product initiative used AVHRR data to produce the first global fire product (April 1992-December 1993) (Dwyer et al., 2000; Stroppiana et al., 2000). The World Fire Web made AVHRR-derived daily global fire maps available on the internet in near real time (Simonetti et al., 2004). Other projects include the World Fire Atlas , the first multi-year global fire atlas, using ATSR-2 (1995-2002) and Advanced ATSR (AATSR) data (2003-present) (Boschetti et al., 2004; Le Page et al., 2008; Mota et al., 2006), also available on the internet in near real time; and the MODIS Active Fire Product starting in 2001, available via the MODIS Rapid Response System and Web Fire Mapper (Chuvieco et al., 2008a; Csiszar et al., 2005; Justice et al., 2002).

Detection of active fires is a task traditionally performed by polar-orbiting sensors mainly, such as AVHRR, MODIS, and ATSR, as mentioned above. However, their time resolution is a problem to operate in real time. New geostationary sensors like the two USA GOES platforms, the European Meteosat Second Generation (MSG), and the Japanese Multifunctional Transport Satellite (MTSAT) are already operational with time resolutions below 30 min, making a real-time global observation network closer to reality (Calle et al., 2006; Calle et al., 2008).

A number of international programs have also mapped burnt area globally. The European Space Agency's (ESA) GlobScar used ATSR data (Boschetti et al., 2004; Simon et al., 2004), while the Global Burnt Area product (GBA-2000) derived its data from the SPOT/VEGETATION sensor. Both projects were limited to the year 2000 (Boschetti et al., 2004). Roy et al. (2005b) described an algorithm developed to map fire-affected areas at a global scale using MODIS surface reflectance time series data, and the results of the first consecutive 12 months of this global burned area product have just been presented (Roy et al., 2008).

Many other national and regional fire programs are also endorsed by GOFC. Reconstruction of fire history over the entire North America is underway by US and Canadian scientists under NASA's Land Use and Land Cover Change Program (Li et al., 2001). The SAFNet (South African Fire Network) is a contributing network to the GOFC/GOLD Fire initiative, using the MODIS active fire and burnt area products, and have developed a protocol for validating the burnt area product (Roy et al., 2005a; Trigg and Roy, 2007).

Since 1998, several services of the European Commission (EC), including the EC Joint Research Center (JRC), have been working to establish the European Forest Fires Information System (EFFIS), which came into effect in 20003, The EFFIS aims to co-ordinate efforts between the various European countries for the first time. Fire risk and burnt area mapping methodologies (using MODIS satellite imagery) in the systems are harmonized at the EU level, which permits the extraction of coherent information for Europe, and the comparison of fire risk and fire damages between European countries or regions (JRC, 2008; San-Miguel-Ayanz et al., 2002). The EU aims to provide environmental information and services that can be combined with other global environmental information products, in support of the Global Monitoring for Environment and Security (GMES) initiative (Fellous, 2008).

In Australia, Satellite Remote Sensing Services at Landgate (the Western Australian Land Information Authority; formerly known as the Western Australian Department of Land Information (DLI), and before that, the Department of Land Administration (DOLA)) is using AVHRR and MODIS imagery operationally to monitor active fires and map burnt areas across the continent through it's FireWatch internet map service (Craig et al., 2002; Justice et al., 2003; Landgate, 2008b). Sentinel is another national bushfire monitoring system providing near real-time internet access information about hotspots to emergency service managers across Australia (Sentinel@ga.gov.au). It was developed by CSIRO Land and Water using the fire algorithm developed by NASA's MODIS Science Team (Justice et al., 2003). GOFC/GOLD provides the framework for Australians to interact with the broader international community, sharing ideas, problems and results, in an effort to improve the operational long-term availability of satellite data for fire monitoring.

But it is not sufficient to simply map individual fire events. This data needs to be analysed over time to define the pattern of fire history or fire regimes for a region.

3.2 Fire Regimes

A fire regime describes how repeated fires disturb a particular site. It includes measurements of fire frequency, fire intensity, extent, season of occurrence and type of fire (Brooks et al., 2004; Gill, 1975). Fire frequency is usually defined as the average time before fire re-burns a given area (also called the fire return interval or fire recurrence interval). Sometimes fire frequency is used to refer to the average time for fire to burn an area equal in size to the given area of interest (also referred to as the fire cycle). Fire intensity is a measure of the amount of heat released per unit of time (while fire severity describes the effect of that heat). Fire extent describes both the size and spatial homogeneity or patchiness of fires. Fire types include ground fire (e.g., peat-bog fires), surface fire (e.g., grass fires), and crown fire (e.g., forest-canopy fires), while seasonality refers to the annual window of fire activity, which is related to the ability of fuels to ignite and carry fire (Brooks et al., 2004).

Fire regimes play a role in the maintenance of vegetation structure and are critical to the survival of some threatened species and ecological communities. There are various methods available in helping to define fire regimes (Gill, 2002). These include:

- Observation (by humans or remote sensing)
- Trees with annual rings and/or fire scars
- Grasstree markings
- Statistical records of government departments
- Maps from departmental records
- Point monitoring
- Use of life history and other attributes of selected plant and animal species
- Quantitative modeling of life history and other attributes of selected plant and animal species
- Palynological and charcoal data

These techniques have been employed widely over the globe in an attempt to enhance our knowledge of fire histories. See table 3.1 for references to some of the more recent research papers.

Statistical relationships between fire regime characteristics and many other factors have been analysed in these various projects. They include climate (precipitation, temperature, lightning, the

Table 3.1 Research papers defining fire regimes

Country	References
The United States	(Baker and Shinneman, 2004; Brown, 2006; Cardille and Ventura, 2001; Chu et al., 2002; Clark and Royall, 1996; Crimmins and Comrie, 2004; Duncan and Schmalzer, 2004; Guyette et al., 2006; Hess et al., 2001; Kasischke et al., 2002; Keeley, 2004; Lynch et al., 2004; Pu et al., 2007; Schmidt et al., 2002; Wells et al., 2004)
Canada	(Ali et al., 2008; Heyerdahl et al., 2007; Kasischke and Turetsky, 2006; Le Goff et al., 2007; Lefort et al., 2004; Pu et al., 2007; Wierzchowski et al., 2002)
Africa	(Heinl et al., 2007; Hudak and Brockett, 2004; Jacobs and Schloeder, 2002; Laris, 2002; Seydack et al., 2007; Thevenon et al., 2003; Van Wilgen et al., 2004)
Europe	(Carcaillet et al., 2002; Colombaroli et al., 2007; de la Cueva et al., 2006; Diaz-Delgado et al., 2004; Pausas, 1999; Vazquez et al., 2002)
India	(Kodandapani et al., 2004; Kodandapani et al., 2008; Saha, 2002)
Cambodia	(Maxwell, 2004)
South America	(Behling and Hooghiemstra, 1999; Cordeiro et al., 2008; Grau, 2001; Kitzberger, 2002; Markgraf et al., 2007; Nepstad et al., 2001; Whitlock et al., 2006)
Russia	(Conard and Ivanova, 1997; Drobyshev et al., 2004; Wallenius et al., 2004)
Australia	See sections 3.2.1 to 3.2.3 below

Palmer Drought Severity Index, El Nino, the Southern Oscillation Index, Pacific Decadal Oscillation, North Atlantic Oscillation and Atlantic Multidecadal Oscillation and atmospheric CO^2 concentrations), vegetation (structure, cover, potential natural vegetation, fuel types and amounts), cause of fire, topography (elevation, aspect, slope), soil conditions, sand deposits, fire risk index, and anthropogenic factors (land cover, land ownership, road network density, fire management).

Giglio et al. (2006) used MODIS active fire observations to estimate global burned area between 2001 and 2004. They proposed it as a useful interim product until long-term burned area data sets from multiple sensors and retrieval approaches become available. Poorest agreement between predicted and observed burnt area was found for southern-hemisphere South America, where predicted values of burned area were both inaccurate and imprecise. Estimates were relatively accurate and precise for Boreal Asia, Central Asia, Europe, and Temperate North America. Chuvieco et al. (2008a) grouped 6 years of global MODIS active fire data by density, season duration and interannual variability. These groups were then compared with biophysical and human explanatory variables, as a first step toward developing a comprehensive global assessment of fire regimes.

The results of the first consecutive 12 months of the NASA MODIS global burned area product were presented recently (Roy et al., 2008), using a method described by Roy et al. (2005b). Total annual and monthly area burned statistics are reported at global and continental scale and with respect to different land cover classes. Globally, the burned area product reports a smaller amount of area burned than the active fire product in croplands and evergreen forest and deciduous needle leaf forest classes, comparable areas for mixed and deciduous broadleaf forest classes, and a greater amount of area burned for the non-forest classes.

The development and validation of a new, global, burnt area product based on SPOT VEGETATION data for seven fire years (2000 to 2007) was reported by Tansey et al. (2008). Correlation statistics between estimated burnt areas are reported for major vegetation types. Validation was undertaken using 72 Landsat TM scenes, showing the accuracy of this new global data set depends on vegetation type.

The first global decadal assessment (1996-2006) of spatial-temporal fire variability using ATSR-2 and AATSR data from the World Fire Atlas was undertaken recently by Le Page et al. (2008). As well as characterising the spatial-temporal patterns of fire activity, they identify broad geographical areas with similar vegetation fire dynamics, and analysed the relationship between fire activity and the El Nino-Southern Oscillation.

There follows a more detailed discussion of the research into defining and analysing fire regimes in Australia, with particular emphasis on the arid and semi-arid regions.

3.2.1 Prehistoric Records

Charcoal concentrations and pollen data from lake, swamp and marine sediments have been used to infer prehistoric changes in the fire regimes of many regions around the world. The research attempts to address the questions of whether changes in fire regimes are caused by human-controlled fire or climatic changes. It also examines how present day regimes relate to the long-term patterns, and the implications of using these long-term data in the formulation of fire management plans to preserve biodiversity. These methods have been used in such diverse areas as Europe (Colombaroli et al., 2007), Europe, South-, Central- and North America, and Oceania (Carcaillet et al., 2002), South America (Behling and Hooghiemstra, 1999; Cordeiro et al., 2008; Markgraf et al., 2007; Whitlock et al., 2006), Cambodia (Maxwell, 2004), the United States (Clark and Royall, 1996), Tanzania (Thevenon et al., 2003), and Australia (Atahan et al., 2004; Black et al., 2008).

There is currently much speculation and contention about the composition of vegetation and the pattern of fire prior to the arrival of Aboriginal people, and the original impact of Aboriginal landscape burning on this environment (Allan and Southgate, 2002; Black et al., 2008; Bowman, 1998). A review of the construction of paleoenvironmental records for Australia by Kershaw et al. (2002) highlights the geographical bias of the data, with a concentration of research in the south east of the country. Such studies are strongly biased against arid and semi-arid environments (Williams, 2002a). Bowman (1998) and Atahan et al. (2004) claim that evidence from charcoal and pollen cores is ambiguous, and pre-human fire regimes are poorly known. Therefore the extent to which post-human regimes vary from these cannot be determined unequivocally. Bowman suggests that we should focus our studies instead, on the role of traditional Aboriginal fire regimes in contemporary ecosystems, for a better comprehension of the part they play in maintaining Australia's unique biodiversity (Bowman, 1998).

3.2.2 Historic Records

The relatively rich records of the early European explorers of Australia have been used in a number of studies, in an effort to reconstruct fire-regimes of Aboriginals before the influence of European colonisation (Bowman, 1998; Vigilante, 2001). While records are geographically biased towards coastal and sub-coastal regions (Russell-Smith, 2002), the use of fire by desert Aborigines was recorded by some explorers in the late 1800’s (e.g. Warburton, Giles and Carnegie) (Burrows et al., 2004). Studies that include desert areas of Australia are one of central Australia (Kimber, 1983), another of Queensland (Fensham, 1997), and a major review of Aboriginal fire regimes in the Western Deserts (Gill, 2000).

Despite the fact that much valuable information has been gained from these sources, there has been some debate over the reliability and validity of the explorers’ records (Bowman, 1998). It is not always clear from the records what kind of fire was sighted (campfire, signal or landscape), their spatial extent or seasonality, whether they were traditional Aboriginal activity or a reaction to the presence of white intruders, or the types of vegetation burnt (Bowman, 1998; Fensham, 1997; Gill, 2000; Vigilante et al., 2004). From his review, Gill (2000) concluded that it is impossible to describe the nature of fire regimes in any specified place in the Western Desert during the ‘traditional’ period. While Burrows et al. (2004) state that “there is limited reliable quantitative information about the nature of the past fire regimes”.

There were practically no anthropological or ecological studies of Aboriginal landscape burning until the latter decades of the 19th century (Burrows et al., 2004). This has resulted in a lack of detailed empirical information on the effects of Aboriginal burning on different environments. While we have lost the opportunity to record traditional knowledge in many of the temperate regions of Australia, remote sensing and geographic information systems provide us with powerful tools for studying those areas which still practice traditional methods of burning (Bowman, 1998).

The arrival of European colonists in Australia resulted in a dramatic shift in human–environment interactions. Aboriginal firing regimes were replaced with new fire regimes associated with wholesale land clearance for agriculture, forestry and mining, as well as numerous and rapid species introductions (Kirkpatrick, 1999). Documentary records can be supplemented with physical evidence. Palaeoecological reconstructions of these changes have been undertaken at the Atherton Tableland of north-east Queensland (Haberle et al., 2006), the lower Hawkesbury Valley, New South Wales (Johnson, 2000), south-west Victoria (Mooney and Dodson, 2001), south-east Australia (Dodson and Mooney, 2002), and South Australia (Bickford et al., 2008; Johnson et al., 2005). Ward et al. (2001) used grasstree analysis to reveal contrasting fire regimes in eucalypt forest before and after European settlement in south-western Australia. All these studies show that the nature and timing of responses of vegetation to European impacts were highly variable in different environments.

Throughout the semi-arid rangelands of Australia, a decrease in perennial grass biomass, resulting from the introduction of grazing animals following European settlement in the 19th century, is thought to have led to a decreased fire frequency and a subsequent rise in unpalatable native woody shrubs (Noble et al., 2007). There is little Palaeoecological evidence for the arid or semi-arid areas (Lunt, 2002) apart from the study by Johnson et al. (2005) at Lake Eyre, South Australia. They used a time series of stable carbon isotope data from emu eggshells, from 11,500 to present, to analyse emu diets. They found that there has been a rapid and dramatic change in vegetation at some point over the last 200 years when compared with the rest of the Holocene. At this changeover approximately 20% of the emu diet changed from grasses to chenopods, shrubs, trees and forbs.

3.2.3 Contemporary Records

Much of the emphasis of research into fire regimes in Australia recently has been on the more fire prone tropical savannas of the north (e.g. (Bowman and Prior, 2004; Bowman et al., 2004; Dawes-Gromadzki, 2007; Edwards et al., 2003; Radford et al., 2008; Russell-Smith, 2002; Russell-Smith et al., 2002; Russell-Smith et al., 2003e; Vigilante et al., 2004; Williams et al., 2002)).

For the vast majority of arid and semi-arid Australia “there is an inadequate record of fires and therefore it is difficult to calculate or describe current fire regimes and impossible to determine change from past times” (Allan, 2003). The limited amount of ethnographic literature includes the works of Gould (1971) on Western Desert Aborigines, and Kimber (1983) on central Australia and the Western Desert, as cited by (Bowman, 1998; Craig, 1999). A more recent project is that of the role of women who hunt with fire in the Mardu tribe of the Western Desert (Bird et al., 2003, 2005). Until recently, the majority of the interior has had no mapped fire history, with analysis being limited in either spatial or temporal extent.

One of the first attempts to characterise the causes, seasonal incidence, distribution and size of wildfires in central Australia was carried out by Griffin et al. (1983). It used records of fires in pastoral areas only (south of the 21st parallel and excluding the Simpson Desert and the Western Desert) which had been reported to the Bushfires Council of the Northern Territory between 1970 and 1980. Each record included date, location, cause, fuel type, estimated size, suppression action and costs incurred. They found that the number of fires in a season was best related to the cumulative rainfall of the preceding 3 years, while the total area burnt was best explained by the rainfall of the preceding 2 years. The distribution of lightning fires was closely related to fuel type and topography.

It is often difficult to obtain accurate information on the fire regime, especially over large and inaccessible areas. Satellite imagery has been used as a data source for some of the fire regime attributes, especially frequency, extent, and seasonality, although there are few methods to measure the intensity of a fire following its occurrence (Kitchin et al., 1998). The application of GIS and remote sensing technologies has rapidly increased our understanding of fire regimes within Australia. But despite arid and semi-arid lands accounting for over two-thirds of the country, little work has been undertaken to define the fire regimes of these regions specifically.

The most extensive spatial database for the arid and semi-arid regions is that of the southern half of the Northern Territory, covering an area of 660,000 km^2. It was first compiled by visual interpretation of Landsat images from the mid 1970’s to 1985 and aerial photographs dating back to 1950. Subsequent annual updates have used NOAA-AVHRR imagery (Allan and Southgate, 2002). This data set has been divided into five sub regions with some of the characteristics measured for each region being:

- Number of times burnt
- Minimum interval between fires
- Mean patch size
- Largest patch burnt
- Number of patches /100 km^2
- Average proportion of region burnt per year
- Apparent fire return period
- Mean proportion burnt per year vs. variance of the proportion burnt per year

(Allan, 2003)

Other Landsat-based databases in the Northern Territory include a 25,239 km^2 area of the Tanami Desert, with a fire history from 1979 to 1996; and a 7,000 km^2 area around Ulura - Kata Tjuta National Park from 1950 to the present (Allan and Southgate, 2002). Kaethner’s honours thesis “Mapping and analysis of fire regimes in the Tanami Desert 2002-2004” also used Landsat imagery (Kaethner, 2004). A number of new databases were also developed as part of the Desert Knowledge CRC project ‘Desert Fire’. King et al (2008c) mapped the fire history for their West

MacDonnell Range study area, between about the mid-1950s and 05/01/2003, from a combination of fire history maps developed in the early to mid-1980s (Grant Allan unpublished data), and more recently from Landsat imagery. For Rainbow Valley Conservation Reserve, all fire plans, reports and paper maps for the reserve from 1984 to 2005 were reviewed, and used to update the GIS record of prescribed burns (which have been mapped since 2000) (Gabrys et al., 2009).

A couple of studies have been undertaken in an area of the Gibson Desert near Lake Mackay. The first covered an area of 540 km^2 using field observations, aerial photos from 1953, 1973 and 1977 and Landsat imagery from 1986 (Burrows and Christensen, 1991). The later study was on a 2,400 km^2 area 80 km to the southwest. This used aerial photography from 1953, Landsat imagery from 1973, 1981, 1988, 1994 and 2000, and field observations (Burrows et al., 2004). These studies compared and contrasted the change in fire patterns since Aborigines had left the area. They found that the small-grained mosaic of burnt patches at different stages of post-fire succession that existed during Aboriginal occupation of the land, has been replaced by a simpler mosaic of either vast tracts of long un-burnt and senescing vegetation, or vast tracts burnt by large, intense and infrequent lightning-caused wildfires.

A database covering 25,000 km^2 of the Great Victoria Desert was first compiled for a Master's thesis (Curry, 1996). Satellite imagery spanned the years 1972 to 1991, but with no imagery available between 1973 and 1978. This data was later used in an analysis of the geometry of the fire scars (Haydon et al., 2000). The size, shape, frequency and inter-spatial relationships of fire scars from over 800 fires were examined. There were on average 43 fires burning between 2 and 5% of the burnable landscape each year. Their average area was 28 km^2 and the average fire return interval was estimated to be at least 20 years.

While all these research projects are very valuable in their own right, their results cannot be directly compared, as they all used different methods of data collection and analysis.

Recently, Landgate (the Western Australian Land Information Authority) has compiled fire history datasets from the relatively coarse (1.1 km resolution) NOAA-AVHRR satellite imagery. These are now available for the Kimberly region back to 1993, the whole of WA back to 1995 and the whole of Australia back to 1997 (Allan, 2003).

They have mapped both fire scars (fire affected areas - FAA) at a 4 km^2 resolution and active fires (fire hotspots - FHS) at a 1 km^2 resolution. A number of studies have utilised this data.

The first was commissioned as part of the Australian Government's State of Environment report. It analysed the distribution, density, extent and seasonality of large fires in Australia from April 1998 to March 2000, using both the FAA and FHS data (Craig et al., 2002). It also related the findings to vegetation type, based on aggregating the 80 Interim Biogeographical Regions of Australia (IBRA)

(Thackway and Cresswell, 1995) into 11 areas referred to as IPR (IBRA Preliminary Regions). While a complete fire regime cannot be inferred from this limited timescale, nonetheless, a number of significant patterns emerged from the two years of data, although there was little detail on desert areas (Craig et al., 2002). Two other papers in this series used the FAA and FHS data for regional analysis of mulga landscapes in central Australia (Williams, 2002a), and north Australian savanna country (Russell-Smith, 2002).

Another major study to use the Landgate data examined contemporary fire regimes of the northern savannas from 1997 to 2001 (Russell-Smith et al., 2003e). It used only the FAA data and examined it in relation to rainfall and seasonality, landuse class, political jurisdiction, broad vegetation type and biogeographic regionalisation. It established that “contrary to recent perception, from a national perspective the great majority of burning in any one year typically occurs in the tropical savannas”

The relationship between fire frequency, rainfall and vegetation patterns in the wet-dry tropics of northern Australia were examined using the FAA dataset from December 1996 to November 2001 by Spessa et al. (2005). The contemporary nature of fire in central Australia has also been examined using this dataset among others (Edwards et al., 2008).

A comprehensive continental assessment of fire patterning from 1997 to 2005 using both the FAA and FHS AVHRR datasets has recently been completed (Russell-Smith et al., 2007b). The longer time frame reinforces the fact that frequent extensive burning occurs predominantly in the savanna landscapes of monsoonal northern Australia, but it also highlighted areas of extensive fire in parts of central Australia. Statistical modelling was used to relate the distribution of large fires to a variety of biophysical variables. This revealed that rainfall seasonality substantially explains the fire patterns at a continental scale. It also implicated the importance of anthropogenic ignition sources, especially in the northern wet–dry tropics and arid Australia, for a substantial component of recurrent fire extent.

The FAA dataset has also been used to estimate biomass burning and greenhouse gas emissions in the savannas (AGO, 2006; Beringer et al., 1995; Meyer, 2004; Russell-Smith et al., 2003b), and the FHS dataset to estimate the area of stubble burning in southern Australia (Smith et al., 2007b).

While not as detailed or accurate as Landsat imagery, the availability of new NOAA-AVHRR data is now providing a valuable and cost-effective insight into the broad regional fire patterns within arid and semi-arid Australia.

Williams (2002a) warns, however, that the coarse resolution of NOAA satellite imagery “is not conducive to monitoring the patchy and often fine-scale distribution of mulga systems” of central Australia, and that “planned fires in conservation reserves in central Australia are generally not detectable by NOAA because these fires are usually small in size and often do not burn overnight.” Likewise, in the savannah regions of northern Australia, fires less than 1 pixel (1 km^2) in size which “constitute by far the great majority of individual fires” could not be detected (Yates and Russell-Smith, 2002).

Despite these drawbacks, we must use whatever information we can to broaden our understanding of fire regimes in our vast interior. It can help to test if generalisations made about desert regimes hold true, or to highlight which areas share similar regimes. Higher resolution Landsat imagery can be used to validate the NOAA data in selected areas or at specific times. The relationship and correlation between many other data sets can also be examined through GIS. There are many potential datasets that could be added to the GIS to improve the analysis of fire regimes. These include:

- Weather (temperature, rainfall, solar radiation, wind)
- Fuel load index (via surrogates)
- Ignition sources (human sources, lightning)
- Land management and ownership
- Vegetation
- Topography
- Soils and geology
- Barriers (water ways, roads)

While the time period of the NOAA-AVHRR data archive is small in terms of human habitation in Australia, there have been recent changes in land management practices which could be assessed with this historical record (Craig et al., 2002).

3.3 Fire Modeling

Fire modeling and information system technology are important in all facets of fire management. Models are used to assess current conditions, to project into the future, and in comparative evaluations of the results of alternative actions of fuel and fire management. They can help assess the risk to life and property and assist policy-makers to plan and carry out fuel management activities. Fire behavior models facilitate fire fighting tactical planning and allocation of scarce resources, both short-term and on a seasonal or yearly basis. Some of the more complicated models can project potential ecosystem changes. Communication between fire managers, policy-makers, and the public are enhanced with models which can provide a visual representation of risk or fire effects (Andrews and Queen, 2001). There has been a considerable amount of research in this area, which cannot be covered fully here.

Fire models are typically composed of fire model equations and fuel models. Fire model equations (often referred to as fire prediction models or fire spread models) are mathematical relationships that describe the complex chemical and physical processes of fire (e.g. forward rate of spread, fire intensity, and flame height). They try to simulate fire behaviour using site-specific data such as weather, terrain, and fuel type and condition, and can include models for ground, surface or crown fire (Albright and Meisner, 1999; Morvan et al., 2002; Perry, 1998).

Fuel models are lists of numbers or parameters that describe the fuel as required by the fire model. A fuel model describes the physical characteristics of the fuel, rather than the species. This allows the user to specify a single fuel model number rather than supplying the individual fuel input values (Allgöwer et al., 2004; Andrews and Queen, 2001; Burgan et al., 1998; Chuvieco et al., 2008a; Cruz and Fernandes, 2008; Keane et al., 2001).

There are several approaches to fire model development (Albright and Meisner, 1999; Andrews and Queen, 2001; Morvan et al., 2002; Perry, 1998). The most commonly used are Physical-Statistical and Statistical.

3.3.1 Physical–Statistical Models

Also known as Semi-Physical or Semi-Empirical, these fire prediction models combine physical theory with statistical correlation from laboratory experiments to generate formulae for fire behavior (Albright and Meisner, 1999; Sullivan, 2008; Weber, 1991).

The most widely used is Rothermel's (1972) model for fire spread in surface fuels, based on the physics of moisture exchange and heat transfer. It was developed for the first National Fire Danger Rating system in the U.S. (Deeming et al., 1972) and is now incorporated into many Decision Support Systems worldwide including South Africa, and Europe (Perry, 1998).

3.3.2 Statistical Models

Statistical (or Empirical) prediction models fit a set of equations to data derived from test fires in the field and observations from unplanned fires (Albright and Meisner, 1999; Cary, 2000; Weber, 1991). These models generally perform well when applied to conditions under which the original data were collected, but extrapolation beyond that range of data may lead to large errors (Andrews and Queen, 2001; Perry, 1998).

McArthur's Fire Danger Meters (McArthur, 1966, 1967; Noble et al., 1980) are used extensively in Australia to describe eucalypt forest or continuous grassland fire behaviour. They are based on more than 800 experimental fires, burning for periods between 15 and 60 minutes, reinforced by observations from a large number of wildfires (Cary, 2000). The results of Project Vesta, a major multi-organisation project investigating high intensity fire behaviour in dry eucalypt forests, are being used to revise the existing forest fire danger rating system (Gould et al., 2008). Experimental burning and associated studies at two sites in the south-west of Western Australia, found the traditional tables of forest fire behaviour to under-predict the potential rate of fire spread in dry forests at higher wind speeds by a factor of up to three-fold.

Fuel moisture content is the main factor limiting ignition and sustained fire spread in continuous fuels. But in patchy fuels such as spinifex, fire spread can only be sustained if conditions are such that the flames from burning hummocks can breach the inter-hummock gaps and ignite the adjacent hummock (Gill et al., 1995). Factors that determine fire intensity, flame size and flame tilt, and therefore the capacity for sustained spread, include wind speed, slope, fuel quantity, fuel moisture content and fuel structural characteristics such as height, cover and patchiness (Burrows et al., 2006c).

A number of models to predict rate of spread in discontinuous spinifex communities have been developed in Australia. These are based on a series of experimental fires at Uluru-Kata Tjuta National Park (Griffin and Allan, 1984), central Australia (Griffin and Allan, 1993), and further research from 41 experimental fires in the Gibson Desert (Burrows et al., 1991).

Griffin and Allan's model for fire rate of spread in spinifex was split into two components. The weather factor, calculated from temperature, relative humidity and wind speed; and the fuel factor, based on the proportions of spinifex cover and bare ground, a patchiness variable and fuel moisture. The Uluru model did not work well in the Gibson Desert when tested. The higher patchiness of fuels here meant that the rate of spread was overestimated. The new model developed for the Gibson Desert used four parameters – wind speed, temperature, ground cover (expressed as a ratio of spinifex cover to bare ground) and fuel moisture. None of these models are currently in use (Allan and Southgate, 2002), but work has continued with a further 42 experimental fires in the Great Sandy Desert (Burrows et al., 2006c).

Fire models can be used as individual models, but may work better as fire management tools, especially for inexperienced users, when packaged into Decision Support Systems. These include the fire model, along with methods of defining and obtaining input and presentation and interpretation of results.

3.4 Decision Support Systems and Predictive Modeling

The packaging of fire spread models as Decision Support Systems varies in accordance with fire management needs. There is a spectrum of predictive modeling from simple, experimental fire behaviour models to complex, process-based fire regime models. Many of them use the same mathematical models for different purposes. For example, Rothermel's (1972) fire spread model is the basis for the BEHAVE fire behavior prediction system, the FARSITE fire area simulator, the

National Fire Danger Rating System (NFDRS), the National Fire Management Analysis System (NFMAS) for economic planning, the Rare Event Risk Assessment Process (RERAP), and many more (Andrews and Queen, 2001; Cary, 2000). There follows a brief discussion of the types of models available for various purposes, with an emphasis on Australian systems, and limited examples and discussion of systems developed overseas.

3.4.1 Fire Growth Simulation

Fire growth simulation (fire potential on a local scale) is the modeling of fire behaviour (e.g. rate of spread, intensity, and flame size) across landscapes with heterogeneous fuels, weather, and topography to predict the final shape and area of a fire event. This type of simulation is used in planning for potential wildland fires, investigating the effectiveness of fuel treatments, prioritizing and locating fuel treatments, tactical support on active fires, and fire incident reconstruction (Finney and Andrews, 1999; Perry et al., 1999).

Table 3.2 Comparison of numerical fire simulation systems

Source: Albright and Meisner (1999)

NOTE:
This table is included on page 75 of the print copy of the thesis held in the University of Adelaide Library.

A fire simulation system generally combines an underlying fire prediction model with a fire simulation technique (table 3.2). Fire simulation techniques are used to represent the spread of fire through the landscape and are classified as Bond Percolation, Cellular Automaton or Elliptical Wave Propagation (Albright and Meisner, 1999).

There are far too many systems to review in this paper, but as an example there follows a brief description of a few systems which all use Rothermel's (1972) model for fire spread prediction, but with different or no simulation techniques:

- BEHAVE
  The BEHAVE Fire Behavior Prediction and Fuel Modeling System (Andrews, 1986), is a simple non-spatial model (i.e. it does not have a fire simulation technique) based on Rothermel's (1972) model for fire spread. Fire fuel type, topography, weather, and initial fuel moisture data for a homogeneous area are input manually. The outputs (spread rates, flame lengths, fireline intensities, and heat calculations) are presented as graphs, tables and reports (Andrews and Bevins, 1999; Andrews and Queen, 2001; Dimitrakopoulos, 2002; Streeks et al., 2005; Vila et al., 2001; Weinstein et al., 1995).

- FARSITE
  FARSITE Fire Area Simulator also utilises Rothermel's (1972) fire spread model (Finney and Andrews, 1999). The fire simulation technique employed is Huygen's principle of wave propagation, which is used to expand surface fire fronts in two dimensions (Weinstein et al., 1995). FARSITE's objective is to simulate a fire as it burns across a highly variable landscape under changing environmental conditions. It utilises GIS data layers of fuels, topography and weather to generate its output of spatial maps of fire growth and intensity. (Albright and Meisner, 1999; Andrews and Queen, 2001; Arca et al., 2007; Finney and Andrews, 1999; Ryu et al., 2007; Stephens, 1998; Xanthopoulos et al., 2002).

- FIREMAP
  FIREMAP (Vasconcelos and Guertin, 1992) integrates the fire spread model of Rothermel (1972), with a raster-based GIS and a cellular automaton simulation technique. Fire characteristics are calculated for each cell and the fire then spreads across a previously computed surface of `frictions'. For this model, `friction' is defined as the time it takes a fire front to consume a cell and is estimated by dividing the rate of fire spread by the cell size (Albright and Meisner, 1999; Perry, 1998).

3.4.1.1 McArthur and CSIRO Fire Spread Predictions

Fire management agencies often use McArthur's Forest or Grassland Danger Meters (McArthur, 1966, 1967; Noble et al., 1980), or the CSIRO's Grassland Fire Spread Meter (Cheney et al., 1998), in planning low intensity prescribed burns, or in simulation exercises to demonstrate the effect of variables like wind speed and fuel load on fire behaviour (Cary, 2000). However, the fire spread predictions (as opposed to fire danger) are rarely used to estimate the forward rate of spread during the high pressure situation of a wildfire. This is due in part to the complexity of calculations, and the number of calculations required to incorporate the effects of topography, and changing fuel types and meteorological conditions (CSIRO, 2001b).

3.4.1.2 SiroFire

SiroFire is a real-time computer application for the prediction of fire spread across the Australian landscape developed by CSIRO's Bushfire Behaviour and Management Group (Coleman and Sullivan, 1996). This fire event simulator predicts the spread of a fire in all directions and plots the perimeter of the fire at specified time intervals. The user can choose from one of five fire spread models:

- McArthur Mk 4 Grassland Fire Danger Meter
- McArthur Mk 5 Grassland Fire Danger Meter
- McArthur Mk 5 Forest Fire Danger Meter
- CSIRO grassland fire spread equation
- Rothermel fire spread equations

Inputs to the model combine a geographic information system (GIS) with real-time data acquisition and data assimilation through modem connections to telephone lines. Information such as temperature, relative humidity, wind speed and direction, fuel load and conditions, grass curing, slope, and the selected fire spread model are used to make the predictions (Beer, 1990; Cary, 2000; CSIRO, 2001b). Outputs are graphical and allow the fire-front position, which is generated using Huygens' principle, to be examined at any desired scale (Beer, 1990).

SiroFire is rarely used to simulate fire spread during a fire event. This is partly due to the lack of the relevant digital data (geographic database and digital elevation model) at the time of the fire. But it has been used by the NSW Rural Fires Service at Wagga and South Australian Country Fire Service in the Adelaide Hills to analyse factors affecting fire spread after fire events. It has also been used as a training tool in simulated fire exercises (Cary, 2000).

3.4.1.3 SHRUBKILL

Ludwig (1988; 1990) describes a simple land management Decision Support System (SHRUBKILL) which is designed to provide advice on the use of prescribed fire to manage shrub problems in semi-arid savanna in eastern Australia. As well as describing fire behaviour, it also provides information on how to plan and safely construct a prescribed fire, advice on whether a burn is needed and an effective time to burn. It also includes a numerical simulation model which computes a cost-benefit analysis for the prescribed fire (Perry, 1998). However, no references to its operational use were found.

3.4.1.4 Griffin and Allan's Spinifex Models

Griffin and Allan (1984) developed a Decision Support System based on their rate of spread model for discontinuous spinifex communities (discussed in section 4.2), to assist park managers at Uluru-Kata Tjuta National Park in central Australia, schedule prescribed burns. A program on a hand held field computer, gives the operator the option of two fire spread models, depending if they are operating in spinifex country or in the grassland and mulga woodlands (or a mixture of both):

- The spinifex model
- McArthur Mk 5 Grassland Fire Danger Meter

They can enter up to five different weather scenarios, with rate of spread predictions calculated for each. The manager can then choose the one which matches the desired outcome best, and perform the burning when these weather conditions are actually met. Despite the versatility, the model was not widely used or tested within parks in central Australia due to the idiosyncrasies of the hand-held computers available at the time (Allan and Southgate, 2002).

This basic model was later expanded to cover a larger area of central Australia under more varied fuel and weather conditions, with the fuel factor based on airborne radiometer data (Griffin and Allan, 1993). It was designed to help in the planning of aerial control burning, but due to the lack of this type of operation in the southern portion of the Northern Territory, and technical issues, once again, this model has not been tested or used. Instead experience and trial and error are used to guide the timing of both prescribed burning programmes and wildfire suppression activities (Allan and Southgate, 2002).

3.4.2 Fire Regime Simulation

The fire regime of an area is defined by its fire type, intensity, severity, size, return interval, seasonality, and distribution of historic and future fires (Duncan and Schmalzer, 2004). Fire, vegetation, and climate are intricately connected and a change in one will ultimately result in a change in another. Climatic change will affect the processes and rates of species growth and thus the rates of accumulation and the composition of fuel loads. The combination of altered fuel loads and altered weather patterns will result in altered fire regimes. Altered fire regimes will in turn affect species growth and community composition (Malanson and Westman, 1991). "One of the most effective tools for studying the relationships between fire, climate, and vegetation is simulation modeling. Although empirical studies are immensely valuable, they are expensive and time-consuming, making them of limited use for characterizing ecosystem change over the large areas and long time spans needed for exploring climate change" (Keane et al., 2004).

Table 3.3 Landscape fire succession models

Source: Keane et al. (2004)

Model name	Reference(s)	Ecosystem	Geographic area	Scale
ALFRESCO	Rupp et al. (2000)	Spruce-fir	Alaska, USA	Coarse
ANTON*	Antonovski et al. (1992)	Boreal Forest	Siberia	Fine
BANKSIA*	Groeneveld et al. (2002)	*Banksia* shrublands	Western	Fine
BFOLDS	Perera et al. (2002)	Mixed boreal	Ontario, CA	Mid
Biome-BGC	Thornton (1998), Thornton et al. (2002)	Any	Global	Coarse
CAFÉ	Bradstock et al. (1998)	Eucalypts	Southern Australia	Fine
CENTURY*	Peng and Apps (1999)	Boreal Forest	Alberta, CA	Coarse
DISPATCH	Baker et al. (1991), Baker (1995, 1999)	Spruce-fir	Central Rockies, USA	Fine
DRYADES	Mailly et al. (2000)	Conifer Forest	Northwestern USA	Fine
EMBYR	Gardner et al. (1996), Hargrove et al. (2000)	Lodgepole pine forests	Central Rockies USA	Fine
FETM	CH2MHill (1998), Schaaf and Carlton (1998)	Conifer Forests	Western USA	Fine
FIN-LANDIS	Pennanen and Kuuluvainen (2002)	Boreal Forests	Fenno-scandinavia	Fine
FIRE-BGC	Keane et al. (1996)	Conifer Forests	Northern Rockies USA	Fine
FIREPAT	Keane and Long (1997)	Any	Western USA	Coarse
FIRESCAPE	Cary (1997, 1998)	Eucalypts Forest	Southeastern Australia	Fine
FLAP-X	Boychuk and Perera (1997), Boychuk et al. (1997)	Boreal Forests	Canada	Fine
FVS-FFE	Reinhardt and Crookston (in press)	Conifer Forests	Western USA	Fine
GLOB-FIR	Thonicke et al. (2001)	Any	Global	Coarse
INTELAND	Gauthier et al. (1994)	Boreal Forests	Canada	Fine
LADS	Wimberly et al. (2000), Wimberly (2002)	Coastal Forests	Pacific Northwest USA	Mid
LAMOS	Lavorel et al. (2000)	Any	Australia	Fine
LANDIS	Mladenoff et al. (1996), He and Mladenoff (1999)	Broadleaf and Conifer	Mid-western USA	Fine-Mid
LANDSIM	Roberts and Betz (1999)	Conifer Forests	Southwestern USA	Fine
LANDSUM	Keane et al. (1997), Keane et al. (2002)	Any	Northern Rockies USA	Fine
MAQUIS*	Perry and Enright (2002)	Maquis Forests	New Caledonia	Fine
MC-FIRE	Lenihan et al. (1998)	Many	Global	Coarse
MOSAIC	Green (1989)	Forests	Australia	Fine
ON-FIRE	Li (1997)	Boreal Forests	Canada	Fine
QLAND	Pennanen et al. (2001)	Boreal Forests	Quebec, Canada	Fine
QTIP*	Plant et al. (1999)	Hardwood and Rangelands	Sierra Nevada, USA	Fine
RATZ*	Ratz (1995)	Any	Alberta, Canada	Fine
REFIRES	Burrows (1988)	Any	Western USA	Fine
REG-FIRM	Venevsky et al. (in press)	Any	Iberia, Europe	Mid
RMLANDS	McGarigal et al. (2003)	Lodgepole Forests	Central Rockies USA	Fine
SAFE-FORESTS	Sessions et al. (1997, 1999)	Mixed Conifer	Sierra Nevada, USA	Fine
SELES	Fall and Fall (1996)	Any	Canada	Fine
SEM-LAND	Li (2000, 2001)	Spruce-fir Forests	Canada	Fine
SIERRA	Mouillot et al. (2001, 2002)	Mediterranean Forests	Southern Europe	Fine
SIMPPLLE	Chew (1997), Chew et al. (in press)	Any	Northern Rockies, USA	Fine
SUFF1*	Suffling (1995)	Boreal Forests	Ontario, Canada	Fine
SUFF2*	Suffling (1993)	Subalpine Forests	Alberta, Canada	Fine
TELSA	Klenner et al. (2000), Kurz et al. (2000)	Any	Western Canada and USA	Fine
VASL	Noble and Gitay (1996)	Forests and Shrublands	Southern Australia	Fine
ZELIG-B*	Cumming et al. (1994), Cumming et al. (1995)	Mixed Boreal Forests	Alberta, Canada	Fine
ZELIG-L*	Miller (1994), Miller and Urban (1999)	Mixed Conifer Forests	Sierra Nevada, USA	Fine

Models without published names were given labels specifically for this study (identified by the asterisk).

There is now a diverse range of over 40 landscape fire succession models available (table 3.3) (Keane et al., 2004). These models generate spatial patterns in fire regime by simulating and overlaying individual fire events that are affected by temporal patterns in the weather and spatial patterns in fuel load dynamics and topography, over a wide range of ecosystems, geographic areas, and spatial scales (Cary, 2000). They are some of the most complicated, time-consuming and costly models to run and can involve fire history sampling, multivariate statistics, remotely sensed image classification, fire behaviour and effects, fuel dynamics, landscape ecology, simulation modeling, and geographical information systems (Keane et al., 2003). Many of these models are still in the realm of research and have not been adopted in daily operations.

It can be seen from table 3.3, that the vast majority operate only on a fine spatial scale, and none have been developed specifically for Australian arid conditions. A number of models which have been (or are likely to be) applied in arid or semi-arid Australia are described below. Other work on fire regime simulation in Australia include studies on banksia (Drechsler et al., 1999; Enright et al., 1998; Groeneveld et al., 2002), native cypress pine (Bowman et al., 2001), a forest ecosystems (seven species) in Tasmania (Su et al., 2001), and the greater glider, an Australian forest-dependent, arboreal marsupial (McCarthy and Lindenmayer, 1999). Beer and Williams (1995) modelled the fire danger index, simulating present conditions and those corresponding to doubled atmospheric CO^2, predicting an increase in fire danger over much of Australia for doubled CO^2.

3.4.2.1 Ngarkat Conservation Park Model

Richards et al. (1999) considered the problem of managing fire in semi-arid Ngarkat Conservation Park (CP), 200 km southeast of Adelaide, South Australia. This is an area of complex sand dunes covered with eucalypt open scrub (mallee) and open heath of sclerophyllous shrubs. It is a key habitat for several nationally rare and threatened species of birds, with preferences for different successional communities. The purpose of this exercise was to show how a mathematical model can be used to help managers determine if the current fire regime is sufficient for promoting community diversity within a reserve, and, if it is not, what management strategies will alter the fire regime so that community diversity is most likely to be achieved. In this exercise, the primary management objective is assumed to be to maintain community diversity within the park by keeping at least 20% of the park in each of three successional stages (early, mid and late). A mathematical model was developed of community succession following a fire disturbance event. The model assumes that each year a manager may do one of the following: let wildfires burn unhindered, fight wildfires, or perform controlled burns. Stochastic dynamic programming was applied to identify which of these three strategies was optimal, i.e., the one most likely to promote community diversity. Model results indicated that the optimal management strategy depends on the current state of the park, the cost associated with each strategy, and the time frame over which the manager has set their goal.

3.4.2.2 CAFÉ

CAFÉ (Cellular Analysis of Fire and Extinction) (Bradstock et al., 1996) is a type of cellular automaton, a spatially explicit model in which events are simulated in discrete time steps and the state of the model at each step depends on its previous state. CAFÉ simulates the population dynamics of a plant species in a fire-prone landscape represented by a grid of square cells. During a simulation each cell can be either vacant or occupied by plants of a specified age. CAFÉ simulations involve setting various life-history and fire-regime parameters, and establishing an initial population in the landscape. The simulation then proceeds in yearly time steps. Fires occur in the landscape stochastically within the parameters set by the user, and the response of the plant population, in terms of dispersal, mortality, and the population size (number of cells occupied), is recorded for each year. The simulation continues until a specified maximum period has elapsed or until no cells are occupied.

CAFÉ was first developed to examine the effect of spatial and temporal variation in fire regimes on the population viability of a fire-sensitive, obligate seeder, Banksia species, which is prominent in fire-prone heathlands of southern Australia (Bradstock et al., 1996). Simulations, 200 years in length, were carried out for mean fire frequencies of 5, 10, 15, 20, 25, and 30 years. Mean values of fire size of 20, 50, and 80% of the grid were explored, along with initial population sizes of 1, 20 and 50% of the grid. Senescence and dispersal were also factored in. Results indicated that interactions between seed dispersal, fire frequency, and size were complex. The model indicated that relying on fire patchiness for species conservation is inadequate. Continual losses of seeds and seedlings to high frequency fires would leave populations with a limited capacity to recover from the inevitable high intensity fires that are part of the fire regime.

Results of 200 year simulations (Bradstock et al., 1998), using the Sydney region as a frame of reference, indicated that reductions in the size of unplanned fires occurred when large (> 30%) areas of the landscape were burnt annually, but that the risk of extinction in obligate seeders was high at such levels of prescribed burning. Extinction probability was also positively related to frequency of unplanned fires.

The CAFÉ model has also been used to examine the persistence of malleefowl in simulated semi-arid mallee shrublands (Bradstock et al., 2005). The model incorporated overlays of animal home ranges, plant populations, landscape features and fires. The spread of fires in this model was governed by a probabilistic flammability function that integrates the effects of fuel accumulation and fire-weather in relation to time-since-fire. Differing flammability functions were specified for the three main topographic categories (swales, dune slopes and dune crests) characteristic of mallee landscapes. Rates of ignition (representative of planned or unplanned fires), spatial patterns (random or non-random) and coincident weather conditions (severe or moderate fire weather) were specified. Results suggested that persistence malleefowl populations will be dependent on intervention using small patchy fires but that there is an optimum rate of intervention. The results were sensitive to spatial pattern of prescribed fire, landscape type (topography) and probability of wildfire. Responses of animals to fires will not only be a function of post-fire change in habitat in each instance of fire, but also indirect cumulative effects of repeated fires on habitat.

More recently (Bradstock et al., 2006), CAFÉ has been used to model the effects of differing fire management strategies on the conifer *Callitris verrucosa* within semi-arid mallee vegetation in Australia, to see whether there are levels and spatial patterns of prescribed ignitions and rates of unplanned ignitions that produce an optimal solution for fire management in mallee landscapes. In this version of CAFÉ fire propagation incorporated the potential for spot fires and the influence of wind direction. In 1,000 year simulations, the lowest population sizes resulted from either high (20% per year) or zero prescribed burning, while the highest population sizes occurred consistently at an intermediate level of prescribed ignition (5% per year). Population sizes were significantly larger in dune vs. flat landscapes and under random vs. non-random prescribed ignition patterns. Prescribed fire is predicted to achieve both a diminution of wildfire size and maintenance of *Callitris verrucosa* population in the landscape. The trade-off required to achieve these objectives concerns the appropriate level and pattern of prescribed fire (strategy).

3.4.2.3 FIRESCAPE

FIRESCAPE, the most well known Australian model, is a fine scale dynamic process-based fire regime simulator (Cary, 1998) which was originally developed for eucalypt forest in southeastern Australia. It uses climatic information, measures of drought and soil dryness, and lightning strike locations to generate spatial patterns in fire regimes (Baker et al., 2000; Cary, 2000).

Each day of the simulation, daily meteorological variables are synthesised from a weather generator. This draws on stochastic models that capture the underlying dynamics of meteorological processes, and the effect of terrain on them, in a particular study area. Daily probability of lightning occurrence and location are determined from empirical models which relate thunder occurrence to aspects of temperature and precipitation in years of daily weather data, and its location to two measures of the terrain related to elevation. Once ignited, fires spread from cell-to-cell according to the elliptical fire spread principles, using an event simulator that is similar to, but less complicated than, SiroFire. Forward rate of spread is predicted by the McArthur Mk 5 Forest Fire Danger Meter. Each ignition, if it spreads, results in a single fire event which is combined with other events to define the spatial pattern of the fire regime. At the end of a simulation, spatial patterns in inter-fire interval, fire line intensity, and season of fire occurrence are determined and mapped. (Cary, 2000)

FIRESCAPE has been implemented in research in the Australian Capital Territory Region of Australia, although not in fire management operations (Cary, 2000). The model suggests that under current climatic conditions the average inter-fire interval for the ACT region is about 27 years on the plains and 50 years in the mountains. The majority of fires occur in summer (76%) with an average fire intensity of 1,800 kW/m. Research to assess fire regimes under the effect of global warming suggests there would be an increase in frequency and possibly also intensity, and a significant shift in seasonal patterns (Baker et al., 2000).

King et al. (2006) re-parameterised this model for the World Heritage Area of south-west Tasmania (FIRESCAPE-SWTAS) to investigate the implications of different prescribed burning treatments on identified management objectives. Simulations identified the nature of the relationships between the prescribed burn treatment level and the fire size distributions, the mean incidence, and the mean annual areas burnt by unplanned fires, with all three parameters declining with increases in treatment level. King et al. (2008b) extended this investigation to additionally explore the effects of prescribed burning treatment unit size on unplanned fire incidence and area burned both in the general landscape and specifically in fire-intolerant vegetation. Simulation results suggest that treatment level had the greatest influence on modifying fire effects, whereas treatment unit size had the least effect.

FIRESCAPE has recently been re-parameterising for arid conditions in the West MacDonnell Ranges, at a 4.1 million hectare study site, about 40 km west of Alice Springs, (King et al., 2008a). The area contains a diversity of vegetation communities, each experiencing different historic fire regimes and having different requirements for fire. There are also a number of land tenure types with differing management objectives. Large fire events in this region are observed predominantly after periods of high rainfall, and this phenomenon has been successfully captured in the model. With minimal further model development, it will be possible to simulate the effects of buffel grass spread, and grazing on pastoral lands on fuel load dynamics and hence on fire regimes for the study area. Further, the effectiveness of alternate fire management practices for parks and Aboriginal lands can be evaluated in light of meeting biodiversity, cultural and property protection objectives. The impact of climate change on fire regimes and management values could also be explored.

3.4.3 Fire Danger Rating Systems

Estimating fire risk or danger involves identifying the potentially contributing variables and integrating them into a mathematical expression, i.e. an index. This index, therefore, quantifies and indicates the level of risk. There are many methods of predicting fire risk leading to various types of indices. Not only can the variables used be different, but also the time and spatial scales.

Some factors only change gradually with time on a long-term perspective, such as slope, aspect, fuel type, climate, location of assets. Long-term fire risk prediction is intended for long term planning, which may serve to characterise regions as subject to high or low risk of fires.

Other factors change rapidly, in a short-term time and space interval, such as wind speed, temperature and fuel moisture (San-Miguel-Ayanz, 2002; San-Miguel-Ayanz et al., 2003; Sebastian-Lopez et al., 2008). Many fire danger rating systems work on a daily time scale at a local level, using these highly variable factors. Short-term prediction is most useful in relation to prescribed burning, fire fighting and fire extinction, and it can be seen as a decision support mechanism for the allocation of resources by operational fire fighting centers (San-Miguel-Ayanz et al., 2002). A fuel map, terrain data, and a reasonable sampling of current local weather conditions are inputs to most short-term fire danger systems.

While in the past most tactical decisions were based on daily fire weather forecasts, there is now a call for longer-range forecasts for strategic planning (Brown et al., 2004). This has come about largely as a response to the record setting blazes of the summer of 2000 in the United States. Following this fire season, the U.S. government established Predictive Services with the vision to "enhance proactive wildland fire management that emphasizes safety, cost containment, efficiency, and ecosystem health" (NIFC, 2002). The concept is to provide seasonal forecasts by integrating climate, weather, situation, resource status and fuels information. These types of long-term forecasts offer a window of opportunity for strategic planning. Preventative measures such as prescribed burning and the creation of firebreaks can be undertaken. These, along with fire fighting readiness, can help mitigate the effects of large, high intensity wildfire seasons.

One of the outcomes of this initiative has been the emergence of a new breed of forecasting model, using statistical regression, for long-lead seasonal wildfire predictions. They use many different techniques and fire-climate relationships. The relationships differ for various regions and must be established for each. Examples of this type of research (predominantly from the U.S.) follow:

- For each of the 11 western United States, statistical models were built from linear correlations and multiple regression of area burned with mean summer temperatures and precipitation, using data from 1916 to 2002 (McKenzie et al., 2004). Projections of future temperature and precipitation for 2070 to 2100 from global climate models were then used in conjunction with these models. While the states showed variations in their sensitivity of fire to climate, for most states they indicated that the mean area burned will be at least doubled by the end of this century, with summer temperature being the most highly correlated variable.

- The Palmer Drought Severity Index (PDSI) is a readily available proxy for soil and fuel moisture. Using data from 1980 to 2000, statistical patterns between monthly PDSI and area burned were established by ecosystem province in the western United States, using Canonical Correlation Analysis (Westerling et al., 2002). Strong negative associations between anomalous soil moisture (inferred from PDSI) immediately prior to the fire season and area burned dominate in most higher elevation forested provinces, while strong positive associations between anomalous soil moisture a year prior to the fire season and area burned dominate in desert and shrub and grassland provinces (Westerling et al., 2002). The forecasting skill of the model to predict a season in advance was established using 'leave one out' cross-validation, i.e. for each time step (year) of the model, a forecast is constructed using all data except the subset for that year. In much of the western U.S., above- and below-normal fire season forecasts were successful 57% of the time or better, with a low probability of being surprised by a fire season at the opposite extreme of that forecast.

- Statistical relationships between monthly ENSO (which relates to sea surface temperatures and pressure systems in the tropical Pacific) data and total area burned and the number of fires were examined using Spearman rank correlations in Hawaii for the period 1976 to 1997 (Chu et al., 2002). Statistical analysis revealed that a large total area burned is likely to occur from spring to summer in the year following an ENSO event. This correlation was used to develop a simple fire-climate model using logistic regression, to test the feasibility of long-lead seasonal fire prediction in Hawaii. The model met with varying levels of success on individual islands

- The approach of Chu et al. (2002) was built upon, by introducing a time series statistical model to predict the severity of the wildfire season (area burned) in Everglades National Park, 3 months and 1 year beforehand (Beckage and Platt, 2003). A time series model has the advantage of being able to account for wildfire activity in preceding years (recently burned areas may not carry enough fuel to burn regardless of conditions). Also it can accommodate evolving changes, as both climate changes and wildfire management alter the observed relationship between wildfire predictors and wildfire occurrence (Beckage and Platt, 2003). Fire records from 1948 to 2001 were used. The 3-month model used correlations between the Southern Oscillation Index (from 3 or more months prior to the midpoint of the spring wildfire season) and area burned in previous wildfire seasons, to predict the area burned in the upcoming wildfire season. The 1-year model only used the area burned in previous wildfire seasons. The area burned in previous time steps predicts area burned in the current time step through autoregressive (AR) coefficients. Using this technique, they were able to accurately model area burned and anticipate severe wildfire seasons.

- Two models have recently been developed to model large scale structural forest fire danger in Southern Europe (Sebastian-Lopez et al., 2008). The physiographic, socioeconomic and environmental factors that best explain fire occurrence in this region were examined using a multi-step analysis based on multiple regression techniques. Using 32 variables in one model, and 37 in the other, the analysis searched for best intermediate models. Statistically, both models performed satisfactorily, with the final fits yielding R^2 values of 0.60 and 0.71.

In the spring of 2003, the first comprehensive seasonal fire potential outlook for the U.S. was produced. These forecasts were formulated at round-table discussions by a team of fire weather meteorologists, fire and fuels specialists, management and climatologists. They incorporated information of past, present and future climate and fuels, and expert knowledge on how they relate to fire activity, as well as results from research such as that just described. Outputs included

NOTE:
This figure is included on page 86 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 3.3 Proposed approaches for the computation of forest fire risk indices

Source: San-Miguel-Ayanz (2002)

geographic area wildland fire outlook reports, a pre-season national wildland fire outlook, and 2003 consensus climate forecasts for wildland fire management (Brown et al., 2004; Garfin et al., 2003).

It is this type of approach which is most suitable for the arid and semi-arid areas of Australia, where the manpower and resources for active fire fighting are extremely limited.

Examples of fire danger rating systems around the world include:

- Canada's Forest Fire Danger Rating System (CFFDRS),
  (Stocks et al., 1989) which is based on moisture physics research, heat transfer theory and observations from 495 experimental fires and wildfires. The Forest Fire Weather Index (FWI) assesses fire danger potential, while the Forest Fire Behavior Prediction (FBP) System predicts fire behavior.
  (Lee et al., 2002; Taylor and Alexander, 2006)

- The National Fire Danger Rating System of America (NFDRS)
  (Deeming et al., 1972), which uses Rothermel's (1972) fire spread model, which is based on the physics of moisture exchange and heat transfer. Major outputs include flame length,

spread rate, energy release, and probability of ignition from a firebrand. (Burgan, 1988; Burgan et al., 1998; Deeming et al., 1977; Hardy and Hardy, 2007)

- Seasonal Wildland Fire Potential Outlooks
  (Garfin et al., 2003) are now being produced for the United States, Canada and parts of Mexico, based on annual workshops by fire, weather, and climate specialists (NIFC, 2008a).

- The European Forest Fire Risk Forecasting System (EFFRFS),
  (San-Miguel-Ayanz et al., 2002) where forest fire risk is evaluated from several perspectives (figure 3.3). There are Structural indices which are updated annually; Dynamic indices where the vegetation status index is computed every ten days and the meteorological index daily; and the Integrated or Advanced index (based on the Fire Potential Index developed for the U.S.A.) which combines these two indices and is updated daily.

3.4.3.1 McArthur's Fire Danger Index

Perhaps one of the simplest fire danger rating systems is that widely used in Australia over the last three decades. The Fire Danger Index (FDI) is based on McArthur's empirical Fire Danger Meters (McArthur, 1966, 1967). Predictions are specific for a particular time and place and are updated daily. It takes into account air temperature; relative humidity; and wind speed measured in the open, long-term drought and recent rainfall. The fire danger index (FDI), on a scale from 1 to 100, is related to the chances of a fire starting, its forward rate of spread, intensity and difficulty of suppression in eucalypt litter with the standard fuel load of 12.5 tonnes per hectare (McArthur, 1967). According to McArthur an index of one (1) means that fires will not burn, or burn so slowly that control presents little difficulty. An index of one hundred (100) means that fires will burn so fast and hot that control is virtually impossible. FDI values are grouped into fire danger classes (low, moderate, high, very high and extreme) (Cary, 2000; Morvan et al., 2002). A similar system is used for continuous grasslands (McArthur, 1966).

3.4.3.2 AussieGRASS

AussieGRASS (Australian Grassland and Rangeland Assessment by Spatial Simulation) is a spatial modelling framework, which has continued to be developed since the late 1980s, to assist in pasture management, natural resource management and policy development (Carter et al., 2000). It estimates pasture growth and total standing dry matter, and how these rate on an historical basis. The outputs are available on a website (www.longpaddock.qld.gov.au) and are updated monthly. A Fire Curing Index and Potential Grassfire Risk are also calculated on a 5 x 5 km grid. While these indices are used by some fire agencies for planning, the monthly estimates do not provide long range predictions.

3.4.3.3 Fire Potential Outlook

A similar approach to the North American Seasonal Wildland Fire Potential Outlooks has recently been adopted in Australia, with the inaugural Seasonal Bushfire Assessment produced for 2006-2007 (Lucas et al., 2006). Each year, following a number of workshops around the country with expert assessments from climatologists, meteorologists and state- based fire-agency personnel; a report and map are produced indicating the fire potential during the active part of the coming fire season for a given region (Bushfire CRC, 2007, 2008; Lucas et al., 2006). It is this type of approach which is most suitable for the arid and semi-arid areas of Australia, where the manpower and resources for active fire fighting are extremely limited.

Apart from the comprehensive assessment of fire patterning for all of Australia from 1997 to 2005 which has recently been published (Russell-Smith et al., 2007b), little statistical analysis of the relationship between fire and its causes has been performed on a continental scale in Australia. This paper revealed that rainfall seasonality substantially explains the fire patterns at a continental scale. It also implicates the importance of anthropogenic ignition sources, especially in the northern wet–dry tropics and arid Australia, for a substantial component of recurrent fire extent. But there is little detail of the processes at work in the arid and semi-arid regions specifically.

Following validation of the NOAA-AVHRR derived fire hotspot (FHS) and fire affected area (FAA) data in arid and semi-arid Australia, and a detailed description of the patterns of fire there between 1998 and 2004, this dissertation will report the results of geo-statistical and exploratory regression analysis. Computational experimentation is used to test how varying model scenarios drive model outcome, in an effort to better understand the spatial and temporal pattern of risk of large, uncontrollable fires in the arid and semi-arid climate zones of Australia. The relative predictability of factors such as climate, weather, vegetation, soil type, tenure (as a surrogate for management strategies), and road and population density on the occurrence of fire is evaluated at a regional scale as well as for the entire study area. The strongest combinations of relationships may be used as spatial indicators in the development of future long-lead fire risk models in the arid and semi-arid regions of Australia.

Chapter 4

A COMPARISON OF NOAA AVHRR FIRE DATA
WITH
THREE LANDSAT DATASETS
IN
ARID AND SEMI-ARID AUSTRALIA

Abstract

Fire hotspot and burnt area data, derived from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) imagery, are validated in 11 regions of arid and semi-arid Australia, using three separate Landsat-derived burnt area datasets.

Mapping accuracy of burnt extent is highly variable between areas, and from year to year within the same area. Where there are corresponding patches in the AVHRR and Landsat datasets, the fit is good. However, the AVHRR dataset misses some large patches.

Most hotspot records have a corresponding burnt area record in the AVHRR and/or Landsat datasets, but have fewer matches in areas of low fire activity. Hotspots do not give a good indication of the area burnt, as many go undetected.

Differences in mapping accuracy between low and high fire years are examined, as well as the influence of soil, vegetation, landuse and tenure on mapping accuracy. Issues which are relevant to arid and semi-arid environments and discontinuous fuels are highlighted.

4.1 Introduction and background

Remote sensing plays an important role in fire and land management, providing timely information on the occurrence and development of fires (Li et al., 2001), while advances in other geospatial information technologies have improved the mapping, modelling and forecasting of fire events. The locations of active fires can be identified from visible smoke plumes, and through automatic processes which identify individual pixels that are hotter than their surrounds. Burnt area (fire scars) can be directly mapped from spectral changes in surface reflectance resulting from deposition of charcoal and ash, and alteration in the structure of the vegetation (Robinson, 1991; Smith et al., 2007b).

There currently exist dozens of algorithms that use different satellite sensors to detect and monitor either active fire (fire hotspots) or burnt area (fire affected area) at the local, regional or global scale. Any fire product only represents a fraction of the total fires which take place both in time and space. This is due to factors such as the low revisit frequencies of the satellites compared to continuous fire activity, non-optimal overpass time, coarse spatial resolution, and atmospheric conditions such as cloud or smoke and particulates from the fire (Eva and Lambin, 1998b; Justice et al., 2002).

The accuracy and limitations of these satellite-derived fire products needs to be determined in a rigorous manner (Congalton, 2001; Justice et al., 2003; Morisette et al., 2005b). Ideally, validation of these products should use an independent source, with a known level of accuracy (“ground truth”), with which to compare the product (Justice et al., 2002; Smith et al., 2007a). In 1998, Eva and Lambin stated that ground truth on fire activity at a regional scale outside Western Europe and North America was difficult to obtain. For coarse resolution imagery in particular, it is often impossible to collect an adequate field dataset with available resources, given the size of the study areas involved.

Eva and Lambin (1998) developed a strategy for assessing the accuracy of burnt area fire mapping derived from coarse scale satellite imagery which involves:

- detailed ground verification exercises (using vehicle or on-ground measurements and aerial transects), preferably at the time of overpasses from higher resolution imagery,

- the generation of a burnt area map from the higher resolution imagery (typically Landsat Enhanced Thematic Mapper Plus (ETM+) or Satellite pour l’Observation de la Terra (SPOT)), and an accuracy assessment of this map using the ground-truth verification data, and

- using the higher resolution burnt area map as a basis for assessing the accuracy of fire mapping derived from the coarser resolution imagery.

The Global Observation of Forest Cover/ Global Observations of Land Dynamics (GOFC/GOLD) Fire Mapping and Monitoring Implementation Team, in a joint effort with the Committee on Earth Observation Satellites (CEOS) Land Product Validation subgroup, now provide a framework for the coordination and standardisation of validation procedures and protocols, and the exchange of validation data between research groups and between fire data producers and users (Justice et al., 2003; Morisette et al., 2002; Rasmussen et al., 2001). Since 2001 they have been establishing a number of long-term active fire and burnt area validation sites around the world, based on recommendations set forth in a white paper by Rasmussen et al. (2001). CEOS members provide high resolution satellite products over the sites, at no or minimal cost. These datasets are validated as far as possible, and accompanied with a statement of their accuracy. They can then be employed to evaluate/validate how methodologies and algorithms from lower resolution products perform in different parts of the world, and relative to each other.

This methodology has now been used for validating a number of burnt area fire products - Moderate Resolution Imaging Spectroradiometer (MODIS) (Roy et al., 2005a), the Advanced Very High Resolution Radiometer (AVHRR) (Collett et al., 2001; Yates and Russell-Smith, 2002) and the Along Track Scanning Radiometer (ATSR) (Simon et al., 2004); as well as MODIS (Morisette et al., 2005a), ATSR and AVHRR (Siegert et al., 1999) active fire products.

In many instances however, validation data with known accuracy are not available. Accuracy assessment of both active fire and burnt area products often involves comparison with available burned area ground survey maps of either prescribed burns or unplanned fires, typically from local or provincial fire authorities, and/or planned or opportunistic aircraft measurements over prescribed burns or wildfires (Boles and Verbyla, 2000; Ichoku et al., 2003; Pu et al., 2007; Swinnen, 2002). Visual inspection of images is also still used in some instances, which enables the detection of systematic under- or over-estimation and confusions with other land cover types (Giglio et al., 2003; Swinnen, 2002).

Common statistical analysis methods used in validation exercises include the error (or confusion) matrix, and linear regression (Eva and Lambin, 1998b; Loboda et al., 2007; Morisette et al., 2005b; Sukhinin et al., 2004; Swinnen, 2002). Other statistical methods include simple measurements of omission and commission (Chand et al., 2006; Gill et al., 2002b; Li et al., 2001; Pu et al., 2007; Roy et al., 2005a; Siegert et al., 1999), the percentage of burnt versus unburnt fine resolution validation pixels within a coarse resolution pixel (Collett et al., 2001; Justice et al., 2002; Kokaly et al., 2007), and detection accuracy by fire size classification (Boles and Verbyla, 2000; Yates and Russell-Smith, 2002).

As part of the Australian Government’s 2001 State of Environment (SoE) reporting, the Western Australian Land Information Authority, Landgate (formerly the Western Australian Department of Land Information (DLI), and before that, the Department of Land Administration (DOLA)) used imagery from NOAA’s AVHRR satellite sensors to map fire hotspots (FHS) at a resolution of approximately 1 km^2, and fire affected areas (FAA) generally greater than 4 km^2, for the entire continent from April 1998 to March 2000. The methodology used is outlined in detail by Craig et al. (2002). The SoE reporting included an analysis of the relationship between the FHS dataset and fires in southwestern Australian Forests recorded by the Department of Conservation and Land Management (CALM) (Gill et al., 2002b), while validation of the FAA dataset was undertaken in five separate regions of the tropical savannas (Yates and Russell-Smith, 2002). A brief analysis of the correlation between the FHS dataset and the FAA dataset was also included in the report by Craig et al. (2002).

These datasets have since been expanded by Landgate, and both are being used operationally to produce publicly available fire locations through their FireWatch map service (Landgate, 2008a).

This paper assesses the accuracy of both the Landgate FAA and FHS datasets between 1998 and 2004 in the arid and semi-arid regions of the continent. There has been no previous published validation of these products in these environments, which account for 70% of the continent. We compare the AVHRR datasets derived from pixels ~1.1 x 1.1 km at orbital nadir, with higher resolution products predominantly derived from 30 x 30 m pixel Landsat imagery. The validation data were sourced from three separate suppliers, and cover 11 sites in Western Australia, the Northern Territory and South Australia.

This analysis assesses the accuracy of AVHRR burnt area (FAA) data by simple measures of omission and commission with all 11 validation site data, and by regression analysis with the better quality validation data, to estimate how well mapped burnt area at the two resolutions match. The AVHRR hotspot (FHS) data are compared to both the AVHRR and Landsat burnt area datasets to estimate how well they have captured the extent of fires. While fire is often a feature in these landscapes (Allan and Southgate, 2002; Hodgkinson, 2002), this timeframe includes a number of years of above average rainfall in some of these areas, which resulted in additional fuel load and subsequent large wildfires (Chapter 5, see also Turner et al., 2008). We examine if years, or areas, of high fire result in better detection rates. We also examine if soil or vegetation type, landuse or tenure can account for differences in detection rates and errors of omission or commission.

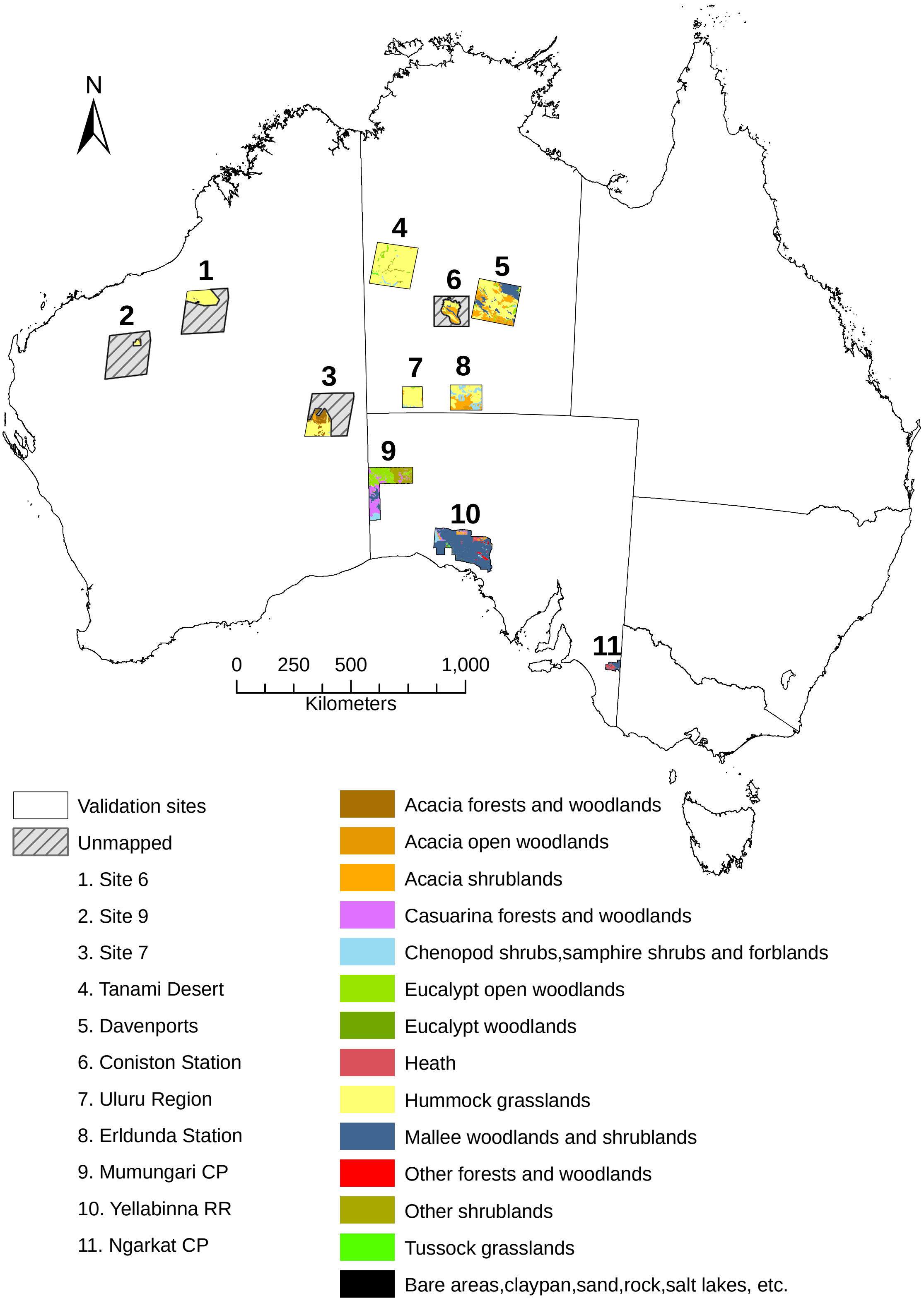


Figure 4.1 Validation sites

4.2 Validation sites

70% of Australia is composed of arid and semi-arid lands. Median annual rainfall ranges from 800 mm in the north to 250 mm in the south, but with extremes of long dry periods and flooding deluges (Bureau of Meteorology, 2005). Soils are characteristically very infertile over extensive

areas (Bureau of Rural Science, 1991), and the vegetation is mainly spinifex hummock grasslands, acacia woodlands and scrublands, and tussock grasslands

(National Land and Water Resources Audit, 2001). Grazing by animals, including termites, generally keeps the fuel loads low on pastoral lands, except after extended periods of widespread rain when growth can far exceed consumption (Hodgkinson, 2002). Aboriginal and vacant crown lands (Stewart et al., 2001) roughly equate to the spinifex-covered sandplains and dunefields and stony deserts which are too unproductive and variable for livestock, but are home to a rich termite and lizard fauna. Spinifex grasses are very flammable, and these grasslands are most regularly and extensively burnt (Allan and Southgate, 2002), with fire frequency correlated to rainfall (Chapter 5, see also Turner et al., 2008).
The choice of validation sites (see figure 4.1) was restricted by the availability of pre-existing higher resolution fire datasets between 1998 and 2004. Three different datasets were sourced, one each from Western Australia, the Northern Territory and South Australia, which represent a diversity of environments within the vast arid and semi-arid areas of the continent.

4.2.1 Western Australia

For Western Australia, Landsat-derived burnt area data from 2001 and 2002, developed for the national MODIS fire products validation program, were provided by Landgate (Western Australian Land Information Authority). Sites 6, 7 and 9 were used in our analysis (see figure 4.1). Only a portion of each Landsat scene had been mapped.

Site 6 is minimal use, vacant crown land on hummock grasslands. These are sandy soils in general, with an area of loams in the south.

Site 7 consists mainly of Aboriginal lands (both reserve and non-agricultural private leasehold) under managed resource protection, and a smaller area of minimal use, vacant crown land. The southern half has hummock grasslands on sandy soils, while acacia forests, woodlands and shrublands on massive and structured earths dominate the north.

Site 9 is primarily private leasehold used for livestock grazing, with an area of minimal use, vacant crown land in the northwest. It consists mainly of hummock grasslands on loams and massive and structured earths, with some acacia forests and woodlands on red duplex soils in the northwest.

4.2.2 The Northern Territory

The Landsat datasets for the Northern Territory were supplied by the Bushfires Council of the Northern Territory (see figure 4.1).

The Tanami Desert Landsat scene is predominantly sand plains with hummock grasslands. There is an area of massive and structured earths in the east. Smaller areas of drainage channels with loams support different vegetation communities. This area is mostly private freehold Aboriginal land, under managed resource protection, with some limited pastoralism on small areas of private leasehold and private freehold land.

In the Davenports area, the central section is composed mostly of hummock grasslands, along with some acacia shrublands. The northeast is dominated by mallee woodlands and shrublands, while the southwest is a mixture of all of these along with some acacia open woodlands and eucalypt open woodlands. The hummock grasslands and mallee occur mostly on sands, while the other vegetation types are predominantly on massive and structured earths. The region is classified as being used mainly for livestock grazing under private leasehold. There are also two non-agricultural Aboriginal areas under managed resource protection.

The Uluru region includes Uluru Kata Tjuta National Park, and the surrounding area of non-agricultural freehold Aboriginal lands under managed resource protection. The vegetation is dominated by hummock grasslands with small areas of acacia shrublands, eucalypt open woodland, and chenopod shrubs, samphire shrubs and forblands. Soils are predominantly sands, with some areas of massive and structured earths.

Coniston Station region is an area of livestock grazing under private leasehold. The vegetation is composed of hummock grasslands on sands, and acacia shrublands mostly on massive and structured earths. There are also some mallee woodlands and shrublands, and eucalypt open woodlands scattered throughout.

Erldunda Station region is also an area of livestock grazing under private leasehold. It is composed primarily of hummock grasslands and acacia shrubland and woodland on sands, and chenopod shrubs, samphire shrubs and forblands on red duplex soils.

4.2.3 South Australia

The Fire History spatial dataset of South Australia, which provides burnt area mapping within or adjacent to conservations parks and reserves, was provided by the Department of Environment and Heritage (Department of Environment and Heritage, 2004). The three areas which accounted for the majority of area burnt within the arid and semi-arid regions between 1998 and 2004 were selected for further analysis (see figure 4.1).

The Mamungari (previously The Unnamed) Conservation Park is based mostly on sand dunes with some areas of calcerous earths. This area has a mixture of eucalypt open woodlands, casuarina forests and woodlands, mallee woodlands and shrublands, and other shrublands.

Yellabinna Regional Reserve is part of the largest expanse of relatively undisturbed mallee in Australia. The underlying soil is predominantly sands, with a little calcerous earths in the southwest.

Ngarkat Conservation Park is composed of a complex of remnant coastal sand dunes that are stabilized by predominantly heath in the west, and mallee woodlands and shrublands in the east.

4.3 Mapping methodology and accuracy assessment of the validation datasets

Burnt area can be directly mapped from spectral changes in surface reflectance resulting from deposition of charcoal and ash, and alteration in the structure of the vegetation (Robinson, 1991).

All burnt area validation data were supplied as polygon or polyline datasets, derived predominantly from 30 x 30 m pixel Landsat imagery (see figure 4.1). The size of the area mapped, origin and quality of the validation data, and timeframes vary between sites (table 4.1). In this section, the fire mapping methodologies used by the suppliers in the creation of the validation datasets are described briefly. So too is the level of accuracy associated with these datasets.

4.3.1 Western Australia

The Landsat validation data (table 4.1 and figure 4.1) provided by Landgate, were compiled following the MODIS burned area product validation protocol for Australia, which was agreed upon at a workshop in Sydney in 2003 (Roy et al., 2003), and based on that developed for South Africa (Roy et al., 2005a). The protocol is based upon interpretations of multi-temporal Landsat Enhanced Thematic Mapper plus (ETM+) data to derive high spatial resolution maps of the location and approximate date of burning.

Mapping was undertaken using proprietary image processing software. Visual interpretation by experts in each region, rather than automated Landsat classification and thresholding techniques, was employed, following the guidelines of the protocol as set out by Roy et al. (2003). Vector datasets were digitized manually that define:

- the boundaries of the mapped region
- burned areas interpreted as occurring between two ETM+ acquisition dates, including any unburned “islands”
- unmapped areas that were not interpreted that fall within the mapped region

Table 4.1 Validation data

Validation site	Area km^2	Data quality	Landsat path / row	Landsat scene dates prefire / postfire	Landsat sensor prefire / postfire
WESTERN AUSTRALIA					
			110 / 75		ETM+ /ETM+
WA site 6	7 939	High		02-12-2001 / 03-01-2002	
WA site 7	10 868	High	106 / 78	02-07-2002 / 19-08-2002	ETM+ /ETM+
WA site 9	773	High	112 / 76	01-11-2002 / 03-12-2202	ETM+ /ETM+
NORTHERN TERRITORY					
Tanami	32 940	High	105 / 74	25-10-2000 / 26-09-2001	ETM+ /ETM+
				26-09-2001 / 08-05-2002	ETM+ /ETM+
				08-05-2002 / 18-12-2002	ETM+ /ETM+
				18-12-2002 / 19-04-2004	ETM+ /TM
				(+ Quicklooks for dating 25-10-2000 to 19-04-2004)	
Davenports	32 971	Medium	102 / 75	04-08-2001 / 21-09-2001	ETM+ /ETM+
Uluru	8 110	Medium	104 / 77-78	12-06-1998 to mid-2004	No details
Coniston	6 226	Low	103 / 75	09-09-2000 / 25-09-2000	ETM+ /ETM+
				09-09-2000 / 11-10-2000	ETM+ /ETM+
				30-12-2000 / 16-02-2001	ETM+ /ETM+
				21-04-2001 / 07-05-2001	ETM+ /ETM+
				07-05-2001 / 23-05-2001	ETM+ /ETM+
				24-06-2001 / 26-07-2001	ETM+ /ETM+
				26-07-2001 / 12-09-2001	ETM+ /ETM+
				28-09-2001 / 14-10-2001	ETM+ /ETM+
				14-10-2001 / 30-10-2001	ETM+ /ETM+
				23-03-2002 / 08-04-2002	ETM+ /ETM+
				26-05-2002 / 27-06-2002	ETM+ /ETM+
				01-10-2002 / 18-11-2002	ETM+ /ETM+
				02-11-2002 / 18-11-2002	ETM+ /ETM+
				18-11-2002 / 06-02-2003	ETM+ /ETM+
				10-09-2003 / 12-10-2003	TM /TM
				10-09-2003 / 28-10-2003	TM /TM
				07-11-2004 / 15-11-2004	ETM+ / TM
Erldunda	15 224	Low	102 / 77-78	12-02-2002 / 16-03-2002	ETM+ /ETM+
				16-03-2002 / 03-05-2002	ETM+ /ETM+
				03-05-2002 / 19-05-2002	ETM+ /ETM+
				04-06-2002 / 07-08-2002	ETM+ /ETM+
				07-08-2002 / 24-09-2002	ETM+ /ETM+
				07-08-2002 / 26-10-2002	ETM+ /ETM+
				24-09-2002 / 26-10-2002	ETM+ /ETM+
				26-10-2002 / 11-11-2002	ETM+ /ETM+
				26-10-2002 / 13-12-2002	ETM+ /ETM+
				11-11-2002 / 13-12-2002	ETM+ /ETM+
SOUTH AUSTRALIA					
Mamungari	21 424	Low	104 / 80	27-03-2001	ETM+
				12-01-2003	ETM+
Yellabinna	30 210	Low	101 / 82	04-01-1999	TM
				17-01-2001	ETM+
				22-03-2001	ETM+
				20-11-2002	ETM+
				06-12-2002	ETM+
				01-12-2003	TM
Ngarkat	2 204	Low	96 / 85	22-03-1999	TM
				12-01-2000	ETM+
				03-03-2001	ETM+
				18-02-1002	ETM+
				19-12-2002	ETM+
				30-05-2004	ETM+
				29-10-2004	TM

As stated in the protocol, the vector line mapping precision is within at least two 30 m ETM+ pixels (i.e. within +/-60 m). The protocol was implemented retrospectively to 2002 data because the Landsat 7 scan line corrector problem, affecting all ETM+ data acquired after May 30th 2003, was not yet present. Because the burns were several years old at the time of mapping, field validation was impractical.

4.3.2 The Northern Territory

The Bushfire Council of the Northern Territory maps fires from NOAA AVHRR imagery on a regular basis for fire monitoring, research and management decision making. To provide more detailed and higher resolution data for specific projects and programmes, the Parks and Wildlife Commission also purchase Landsat images every three to four months for fire scar mapping (Walsh et al., 2006). There can be considerable variability in the mapping methods used (Edwards et al., 1999; Walsh et al., 2006). These techniques vary between vector or raster based delineation, either automatically, manually or a combination of both.

No indication of the methodology used, or the level of accuracy, was provided with the Northern Territory data, apart from the Tanami Desert scene (table 4.1 and figure 4.1).

The Tanami Desert validation site was used to map and analyse fire regimes using Landsat imagery between 2000 and 2004 (Kaethner, 2004), as part of a biodiversity monitoring programme proposed by Newmont Australia, a gold mining company in the area, and the Central Land Council. A combination of principal components analysis of multi-date images, unsupervised classification, and visual inspection were used in identifying and mapping burnt areas. The archive of JPEG Quicklooks available from the Australian Centre of Remote Sensing was then used to assign dates to the mapped fires (Kaethner, 2004). To validate the mapping, 54 on-ground burnt area edge tracks were recorded with a GPS by following them on foot or in a vehicle. Analysis showed that the mapped fire edges are accurate to a mean distance of 22.7 m (less than one Landsat pixel) either side of the actual fire edges (Kaethner, 2004).

The data supplied for the Davenports has fine detail, including internal unburnt islands. It does not preserve the original pixelation of the Landsat imagery, but smoothes and generalizes the fire scar edge. In the Uluru region also, the mapped fires have good detail and show internal patch heterogeneity. A number of mapping methodologies were used, however. Records before 2003 retain pixelation. The ‘pixels’ are at a 20 m resolution in the pre 2002 data, and 12.5 m in the 2002 data. Records after 2002 are more generalized, and do not retain pixelation. Both the Coniston Station and Erldunda Station fire affected areas were mapped using generalized vector based outlines, with little detail and no internal islands.

4.3.3 South Australia

The Fire History spatial dataset of South Australia provides fire scar mapping for many major fires that have burnt largely within or adjacent to National Parks and Wildlife South Australia (NPWSA) parks and reserves. Small fires may not have been mapped (Department of Environment and Heritage, 2004). Only the perimeters of the fire scars were mapped and so the fine detail is lost (table 4.1 and figure 4.1).

The data between 1998 and 2004 for the Mamungari Conservation Park were digitized at 1:100 km from orthorectified Landsat 7 ETM+ imagery. That for Yellabinna Regional Reserve was digitized from Landsat 5 TM (Thematic Mapper) and Landsat 7 ETM+ imagery. Some Ngarkat Conservation Park fires were digitized from Landsat 5 TM imagery, others from orthorectified aerial photography at 1.1 km to 1.8 km, and the rest from unspecified sources.

4.4 NOAA AVHRR burnt area mapping accuracy assessment

The NOAA AVHRR sensor, with ~1.1 x 1.1 km resolution at orbital nadir, is now being used operationally to map fire affected areas (FAA) for the entire Australian continent by Landgate (Western Australian Land Information Authority) (Justice et al., 2003; Landgate, 2008a). The raw AVHRR data are geometrically and radiometrically corrected using Common AVHRR Processing Software (CAPS). Mapping involves a semi-automated process of on-screen digitizing of fire-scars, determined from visual interpretation of changes in the visible, near infrared and thermal bands (bands 2, 3, and 5) of daytime imagery (Craig et al., 2002). This occurs every nine days of the repeat orbital cycle where possible, to minimize angular effects.

This section assesses the accuracy of the FAA dataset, with reference to the three different Landsat datasets, across the 11 validation sites, using a number of different approaches.

4.4.1 Methodology

4.4.1.1 Pre-processing

The AVHRR burnt area data were supplied by Landgate (Western Australian Land Information Authority) as polygon datasets for the entire country from 1998 to 2004 inclusive. These, along with the validation data, were imported into proprietary Geographic Information System (GIS) processing software. Further processing took place within this system, along with a proprietary statistics package.

For each of the 11 sites, a subset of the AVHRR dataset covering the same spatial and temporal extent as the validation data was extracted. Manual examination of the spatial data showed a clear correspondence between the AVHRR and Landsat records in most cases. Because of the different dates of image acquisition however, there could be a difference between the times a burnt area was identified in each dataset. Records were accessed manually on an individual basis, and generally considered a match if they overlapped spatially and fell within a three month lag time.

In arid and semi-arid Australia, there is great variation in the amount of area burnt from year to year, dependant largely on antecedent rainfall (Chapter 5, see also Turner et al., 2008). The mapped fires at the Western Australia validation sites occurred following annual rainfall above average by 500 mm (site 7 and 9) to 900 mm (site 6) in the previous year (Bureau of Meteorology, 2005). The first two Tanami fire years followed rainfall above average by 300 mm – 650 mm in 2000 and 2001, while the low fire year came after rainfall up to 200 mm below average in 2002 and 2003. 2000 and 2001 were also years of above average rainfall (+300 mm to +600 mm) for the other Northern Territory sites, and Mamungari in South Australia. In Yellabinna and Ngarket, rainfall ranged less than 100 mm above or below average for the years in question.

To examine the variability of mapping accuracy between high and low fire years, those datasets which covered more than one fire season were divided into fire years.

The Landsat mapping of the Tanami Desert from Kaethner’s study (2004) covers a period of three and a half years. It consists of composited maps of annual burns where fires are classified by month and year. Examination of this data and the AVHRR subset showed that natural breaks could be identified, where no corresponding fire scars from one dataset would be present in a different “year” in the other dataset. Based on this, records from both datasets were divided into three fire years defined as follows:

- 05-2001 to 04-2002
- 05-2002 to 02-2003
- 03-2003 to 03-2004

The Uluru data were divided into three timeframes as follows:

- 1998 to 2001
- 2002
- 2003 to 2004

The data for the Coniston Station area was processed by calendar year, while the South Australia data were divided from July of one year to June of the next.

4.4.1.2 Errors of Omission and Commission

Typically, remote sensing accuracy assessment is summarized through an error matrix. However, for such an analysis, the reference or validation data should be collected at the same minimum mapping unit as the map that is being assessed (Congalton and Green, 1999). It is therefore inappropriate to produce an error matrix directly comparing the AVHRR and Landsat data, as they are sampled at different resolutions.

Instead, a simple comparison of mapped burned areas was performed between the AVHRR data and the validation data within the GIS. For each validation site (and for each year where appropriate), the data were classified as either mapped in both datasets, mapped in the Landsat dataset only (omission errors), or mapped in the AVHRR dataset only (commission errors), and the areas of each calculated.

4.4.1.3 Regression Analysis

This analysis involves using two sets of data with different resolutions, which correspond in both area and dates, and establishing the relationship between them. By measuring the proportion of area burnt within much larger grid cells, a regression can be computed (Eva and Lambin, 1998b; Yates and Russell-Smith, 2002).

Regression analysis was only performed with the validation data which included mapping of internal patch heterogeneity (i.e. for each of the three Western Australian validation sites and for each of the three years at the Tanami Desert sites). A grid of 10 x 10 km cells was created for each validation site and the percentage of area mapped as burnt in each of the grid cells was calculated for both the Landsat and AVHRR fire data within the GIS. These results were exported into a statistics package, where for each scene and year, a linear regression was performed. The ‘true’ extent of burning, as estimated from the Landsat data, was predicted against the AVHRR burnt area data.

4.4.2 Results

4.4.2.1 Errors of Omission and Commission

Table 4.2 and figures 4.2-4.4 show the relationships between the Landsat and AVHRR burnt area mapping. Overall, 63% of the Landsat burnt area was also mapped in the AVHRR dataset, but varied from 0% to 89%. In total, 81% of the AVHRR burnt area data was matched in the Landsat dataset, again ranging from 0% to 94%. The lower match rates (<50%) were generally where little area had burnt (0-500 km^2), apart from Yellabinna. Figures are better generally in the more northerly sites, and although site 9 and Coniston in 2004 had little fire, there was good agreement with the validation datasets. Yellabinna in the south, on the other hand, had over 2 000 km^2 of Landsat-based burnt area without any matching AVHRR patches.

In Western Australia (table 4.2 and figure 4.2), both sites 6 and 9 show a high degree of agreement in the general shape and location of mapped fires in the two datasets. Over 85% of the area mapped

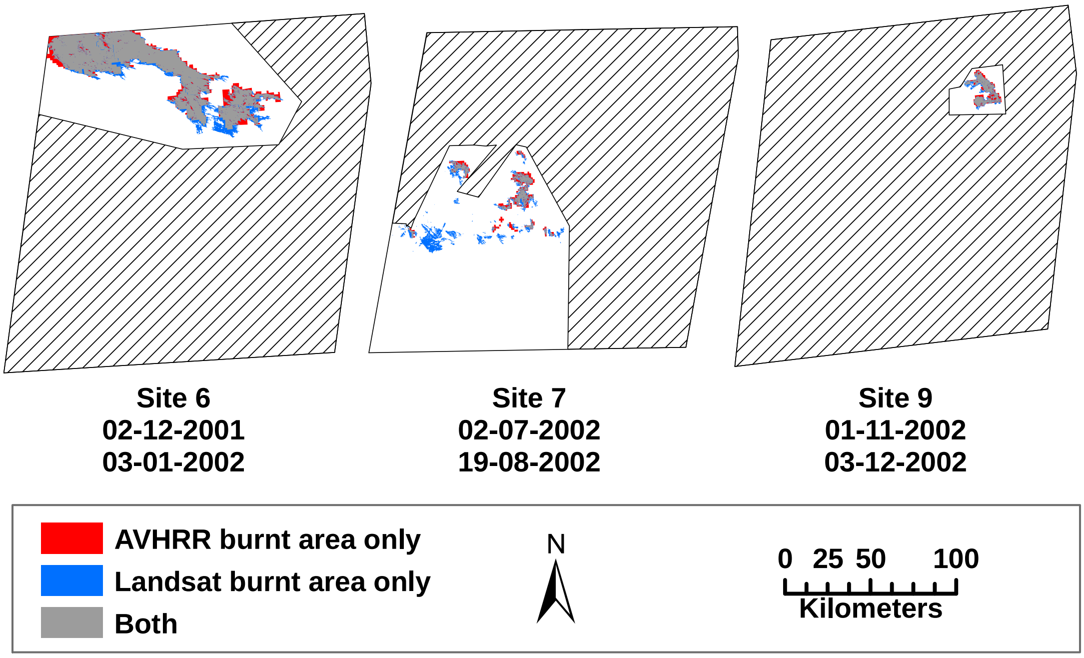


Figure 4.2 Western Australia - Comparison of AVHRR and Landsat burnt areas

from the Landsat imagery was also mapped in the AVHRR dataset, and between 70% and 85% of the area mapped from AVHRR was also mapped from Landsat imagery.

Site 7 does not match as well. Over 60% of the Landsat burnt area was not detected from the AVHRR data, with a number of fires having no corresponding AVHRR record. But for the 45% of site 7 AVHRR burnt area not also mapped from Landsat, most is due to the AVHRR data that extends beyond the Landsat burnt area by only one AVHRR pixel (1 km).

In the Tanami, the first two years were very high fire years with many large fires, while the third year had only a few, much smaller, fires. The results are displayed in table 4.2 and figure 4.3. Overall 44% of the area of Landsat fires were not detected in the AVHRR imagery, and 25% of the area of AVHRR fires were not mapped in the Landsat dataset, but there was considerable variation between years. There were a number of large burnt areas in the first two years that were not detected in the AVHRR data. These can be seen in the Landsat JPEG Quicklooks, but there is considerable cloud cover around those in the west in year one. Those in year two were generally the scars with a brighter colour in the Quicklooks. Errors of commission, on the other hand, are due largely to the difference in scale between the datasets, and are generally within one AVHRR pixel of the Landsat burnt areas, apart from one AVHRR patch which may have been mapped in error (see discussion section 7 below). There are also a few small areas with no intersecting Landsat data. While the percentages were worse in the third year, the omission and commission errors were much smaller in area.

Table 4.2 Comparison of Landsat and AVHRR burnt areas

		Total burnt area		Mapped in both datasets			Landsat only		AVHRR only	
Validation Site	Approx. dates	Landsat km^2	AVHRR km^2	Area km^2	Landsat %	AVHRR %	km^2	%	km^2	%
				WESTERN AUSTRALIA						
WA site 6	12/01	2 141	2 174	1 858	86.8	85.5	283	13.2	316	14.5
WA site 7	07-08/02	445	318	174	39.1	54.7	271	60.9	144	45.3
WA site 9	11-12/02	149	180	126	84.6	70.0	23	15.4	54	30.0
WA total		2 735	2 672	2 158	78.9	80.8	577	21.1	514	19.2
				NORTHERN TERRITORY						
Tanami	2001-2002	9 115	5 751	4 528	49.7	78.7	4 587	50.3	1 223	21.3
	2002-2003	10 754	8 946	6 693	62.2	74.8	4 061	37.8	2 253	25.2
	2003-2004	321	206	113	35.2	54.9	208	64.8	93	45.1
	Total	20 190	14 903	11 334	56.1	76.1	8 856	43.9	3 569	23.9
Davenports	08-09/01	8 563	6 944	6 175	72.1	88.9	2 388	27.9	769	11.1
Uluru	1998-2001	185	42	9	4.9	21.4	176	95.1	33	78.6
	2002	5 274	5 385	4 571	86.7	84.9	703	13.3	814	15.1
	2003-2004	36	17	0	0.0	0.0	36	100.0	17	100.0
	Total	5 495	5 444	4 580	83.3	84.1	915	16.7	864	15.9
Coniston	2000	592	650	528	89.2	81.2	64	10.8	122	18.8
	2001	2 228	1 504	1 297	58.2	86.2	931	41.8	207	13.8
	2002	984	965	632	64.2	65.5	352	35.8	333	34.5
	2003	144	67	47	32.6	70.1	97	67.4	20	29.9
	2004	245	305	188	76.7	61.6	57	23.3	117	38.4
	Total	4 193	3 491	2 692	64.2	77.1	1 501	35.8	799	22.9
Erldunda	2002	5 609	4 654	4 378	78.1	94.1	1 231	21.9	276	5.9
NT total		43 990	35 414	29 045	66.0	82.0	14 945	34.0	6 369	18.0

Table 4.2 Continued

		Total burnt area		Mapped in both datasets			Landsat only		AVHRR only	
Validation Site	Approx. dates	Landsat km^2	AVHRR km^2	Area km^2	Landsat %	AVHRR %	km^2	%	km^2	%
				SOUTH AUSTRALIA						
Mamungari	2000-2001	2 911	1 404	1 166	40.1	83.0	1 745	59.9	238	17.0
	2001-2002	0	12	0	-	0.0	0	-	12	100.0
	2002-2003	4 116	4 077	2 938	71.4	72.1	1 178	28.6	1 139	27.9
	2003-2004	0	67	0	-	0.0	0	-	67	100.0
	Total	7 027	5 560	4 104	58.4	73.8	2 923	41.6	1 456	26.2
Yellabinna	1998-1999	12	0	0	0.0	-	12	100.0	0	-
	1999-2000	0	0	0	-	-	0	-	0	-
	2000-2001	0	0	0	-	-	0	-	0	-
	2001-2002	1 866	0	0	0.0	-	1 866	100.0	0	-
	2002-2003	133	13	0	0.0	0.0	133	100.0	13	100.0
	2003-2004	87	0	0	0.0	-	87	100.0	0	-
	Total	2 098	13	0	0.0	0.0	2 098	100.0	13	100.0
Ngarkat	1998-1999	679	656	567	83.5	86.4	112	16.5	89	13.6
	1999-2000	1	0	0	0.0	-	1	100.0	0	-
	2000-2001	1	0	0	0.0	-	1	100.0	0	-
	2001-2002	38	1	0	0.0	0.0	38	100.0	1	100.0
	2002-2003	263	0	0	0.0	-	263	100.0	0	-
	2003-2004	3	0	0	0.0	-	3	100.0	0	-
	2004-2005	44	0	0	0.0	-	44	100.0	0	-
	Total	1 029	657	567	55.1	86.3	462	44.9	90	13.7
SA total		10 154	6 230	4 671	46.0	75.0	5 483	54.0	1 559	25.0
Grand total		56 879	44 316	35 874	63.1	81.0	21 005	36.9	8 442	19.0

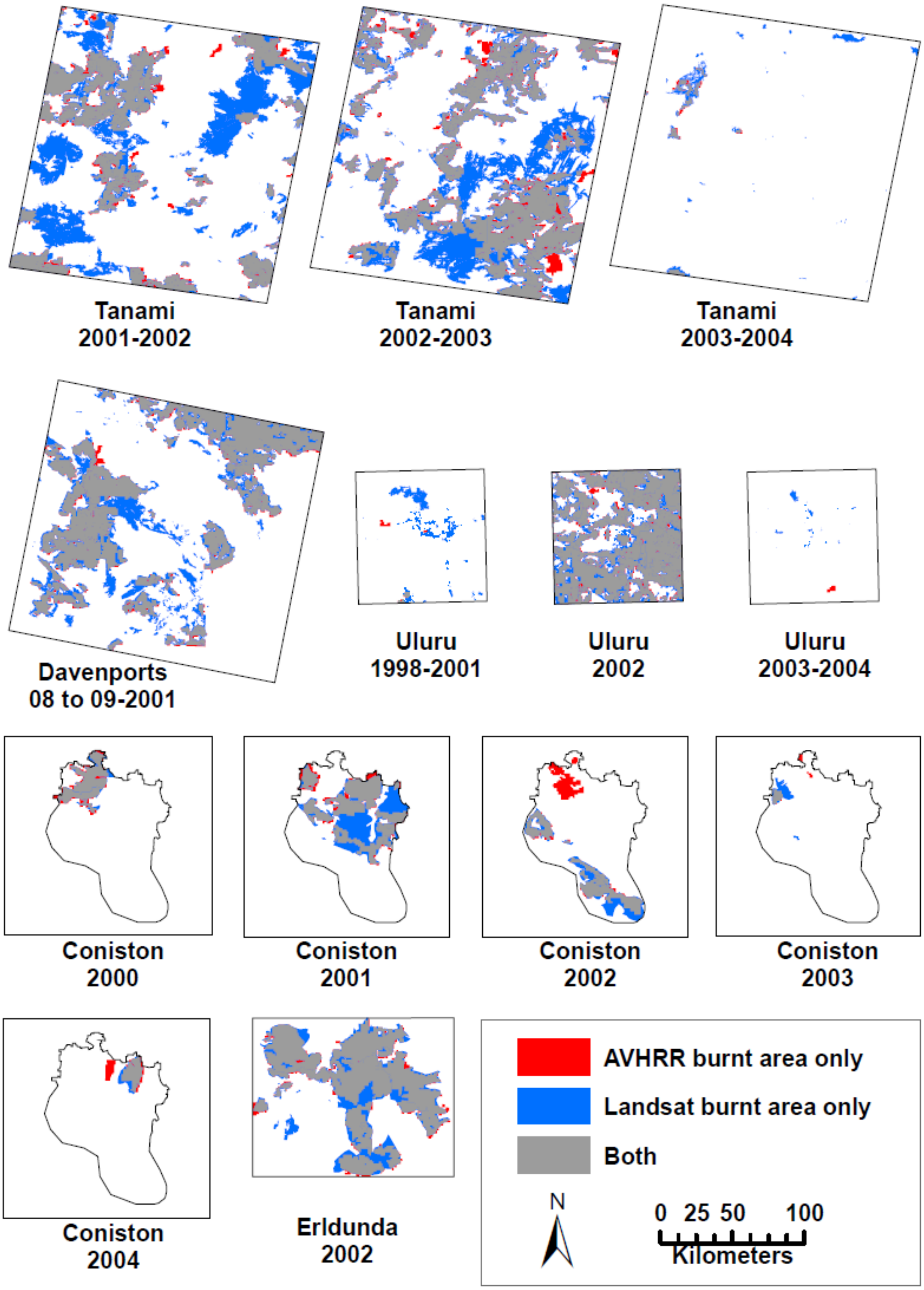


Figure 4.3 Northern Territory - Comparison of AVHRR and Landsat burnt areas

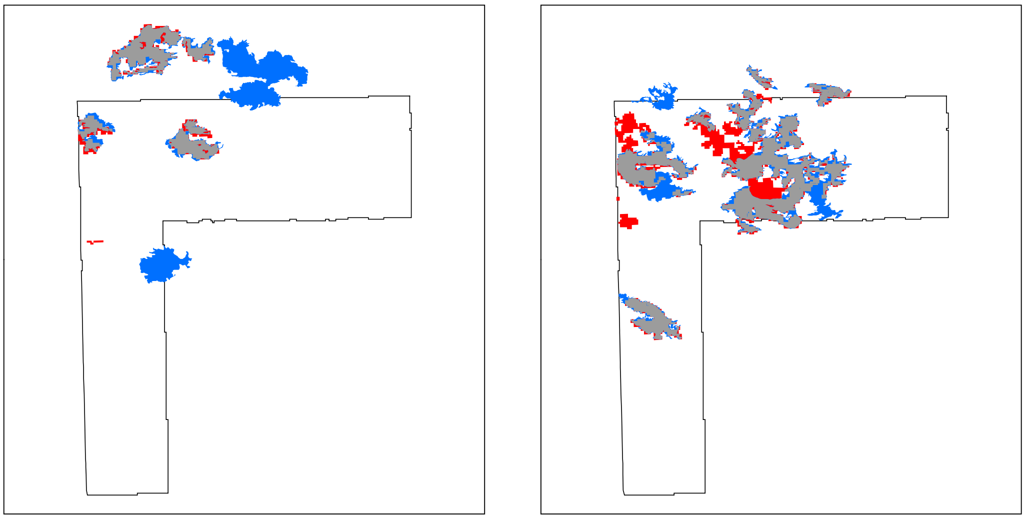
Approximately 25% of the Davenports validation site was burnt between August and September 2001. There is a reasonable fit of the AVHRR to the Landsat dataset (table 4.2 and figure 4.3), but with about one quarter of the burnt area mapped by Landsat only. On the Landsat Quicklooks, the unmapped areas are either lighter in colour or obscured by smoke. The small amount mapped from AVHRR only, is primarily a result of the coarser scale resolution of this dataset.

The results from Uluru National Park Region can be seen in table 4.2 and figure 4.3. In 1998 and 1999 there were 74 management fires and two wildfires that were mapped in the Landsat dataset. Together these totaled just over 1 km^2 of burnt area. None of these small fires were detected in the AVHRR data. Between 2000 and the end of 2001, a further 184 km^2 of burnt area was mapped from Landsat imagery, but with little corresponding AVHRR burnt area. There is no overlap between the Landsat data and the two AVHRR records from 2000, but both 2001 AVHRR records intersect with Landsat mapping quite well. The picture from the 2002 wildfires is quite different, when approximately 65% of the validation site burnt (over 5 000 km^2). There is very good agreement between the two datasets, although specific dates cannot be matched as the Landsat data only identifies the year. Around 15% of each dataset was not mapped by the other, with much of this simply due to the differences in scale between them. In 2003 and 2004 four burnt areas over 1 km^2, and over forty smaller patches, were mapped from Landsat imagery totaling just 36 km^2. There is one 17 km^2 AVHRR burnt area from 2003, but this does not correspond to any of the Landsat patches.

For the remaining validation data, not as much confidence can be placed in the results, as the validation data is not of as high a quality. It does still give some indication of whether the AVHRR sensor is capturing fires in these environments, however.

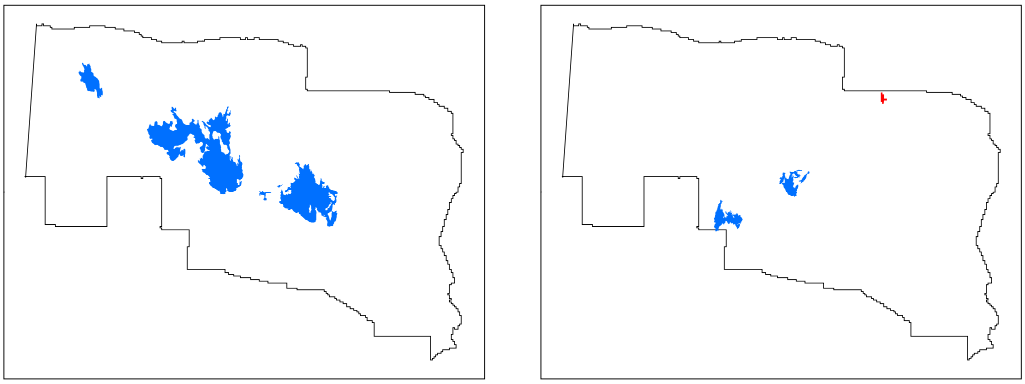
In the Coniston Station region (table 4.2 and figure 4.3) the majority of burnt area was captured in both datasets. However there are some reasonable sized areas that were not mapped in one or other of the datasets, amounting to 36% of the Landsat, and 23% of the AVHRR burnt areas. The general outlines of the datasets match reasonably well in the Erldunda Station region (table 4.2 and figure 4.3), but there is more large scale fragmentation within the AVHRR data. Examination of the Landsat Quicklooks for both these sites indicates that the areas not mapped from AVHRR imagery were less severely impacted by fire, with less obvious scaring that is more fragmented than the areas common to both datasets. The true area burnt is somewhat less than that mapped in the Landsat dataset. From checking the Landsat Quicklook images, the commission patch in the Coniston 2002 scene, does appear to be a burnt area that was not mapped in the Landsat dataset, while the 2004 commission patch is not visible in the Landsat Quicklooks.

The results for South Australian Parks and Reserves are displayed in table 4.2 and figure 4.4. There was quite a variation between years for the Mamungari Conservation Park. In the 2000-01 season, the majority (60%) of Landsat burnt area was not detected in the AVHRR dataset. The 2002-03



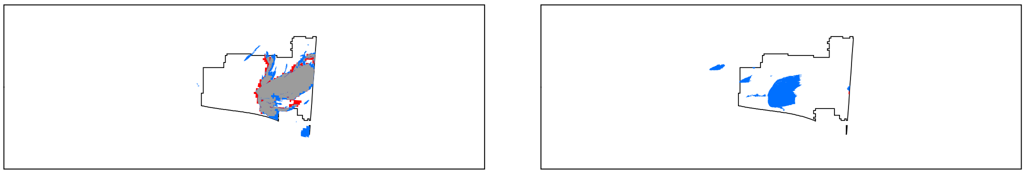
Mamungari
1998-2002

Mamungari
2002-2004



Yellabinna
1998-2002

Yellabinna
2002-2004



Ngarkat
1998-2002

Ngarkat
2002-2004

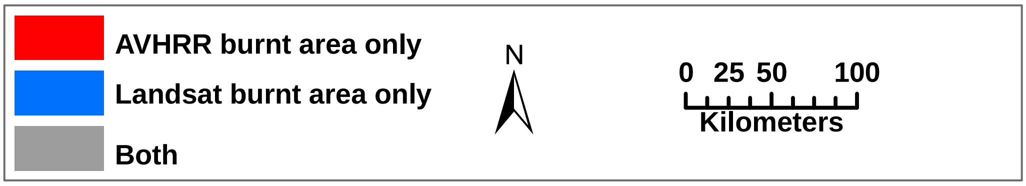


Figure 4.4 South Australia - Comparison of AVHRR and Landsat burnt areas

season provided a better fit, with over 70% mapped by both, and almost 30% of each not mapped by the other. The unmapped AVHRR patches were visible in some Landsat Quicklooks, but many of the images were affected by cloud. The fairly large AVHRR-only burnt areas in 2002-03 raise some questions however (see results section 5.2. and discussion section 7). In the Yellabinna Regional Reserve, over 2 000 km^2 burnt area was mapped from the Landsat imagery. These fires are very obvious in the Landsat Quicklook images as bright pink patches. Only one ~13 km^2 patch was mapped from AVHRR imagery, and it had no corresponding Landsat patch. In Ngarkat Conservation Park, there was a very good correlation between the Landsat and AVHRR 1998-99 fires, but no corresponding AVHRR burnt areas in the other three seasons. Once again, all fires can be seen in the Landsat Quicklooks.

4.4.2.2 Regression Analysis

The results of the regression analysis are presented in table 4.3 and figure 4.5. The number of 10 x 10 km cells ranged from 10 in site 9, to 368 in the Tanami Desert scenes. There was also a vast range of results in the data examined, with the Western Australian sites providing both the worst (0.37) and best (0.96 and 0.94) r^2 values. For the Tanami Desert scene, regression analysis was performed on each year of data. The fit again varied greatly from a poor r^2 of 0.41 in the first year to a more respectable 0.61 in the third year. The slopes of all regressions indicate that the mapping from AVHRR under-estimated the 'true' extent of burning for all scenes and years. These results generally support the findings from the analysis of errors of omission and commission above (apart from year three in the Tanami, which has the highest r^2 value (0.6) for this scene, but the lowest % of common mapped burnt area (35%)).

Results of regression, where the intercept is set to 0, are also shown in table 4.3. These can be used for direct comparison with the validation results for northern Australia (Yates and Russell-Smith, 2002). When all the data were analysed together (table 4.3) it resulted in an overall r^2 of 0.60 (or 0.56 with the intercept set to 0).

Table 4.3 Western Australia and Tanami Desert. Estimates of the extent of burning as derived from AVHRR and Landsat imagery, for each 10 x 10 km grid cell

Validation site	Approx. dates	# cells	r^2	Regression equation	r^2 when intercept = 0	Equation when intercept = 0
WA site 6	12/01	85	0.9358	0.9559x + 0.6488	0.9356	0.9695x
WA site 7	07-08/02	116	0.3739	0.7271x + 1.8408	0.3385	0.8017x
WA site 9	11-12/02	10	0.9597	0.8038x + 0.5049	0.9591	0.8173x
Tanami	2001-2002	368	0.4139	0.7149x + 13.436	0.2558	0.9446x
	2002-2003	368	0.5551	0.7376x + 11.364	0.4636	0.9274x
	2003-2004	368	0.6052	0.9516x + 0.6052	0.5997	0.9669x
Totals		1 315	0.5995	0.8309x + 6.2982	0.5558	0.9375x

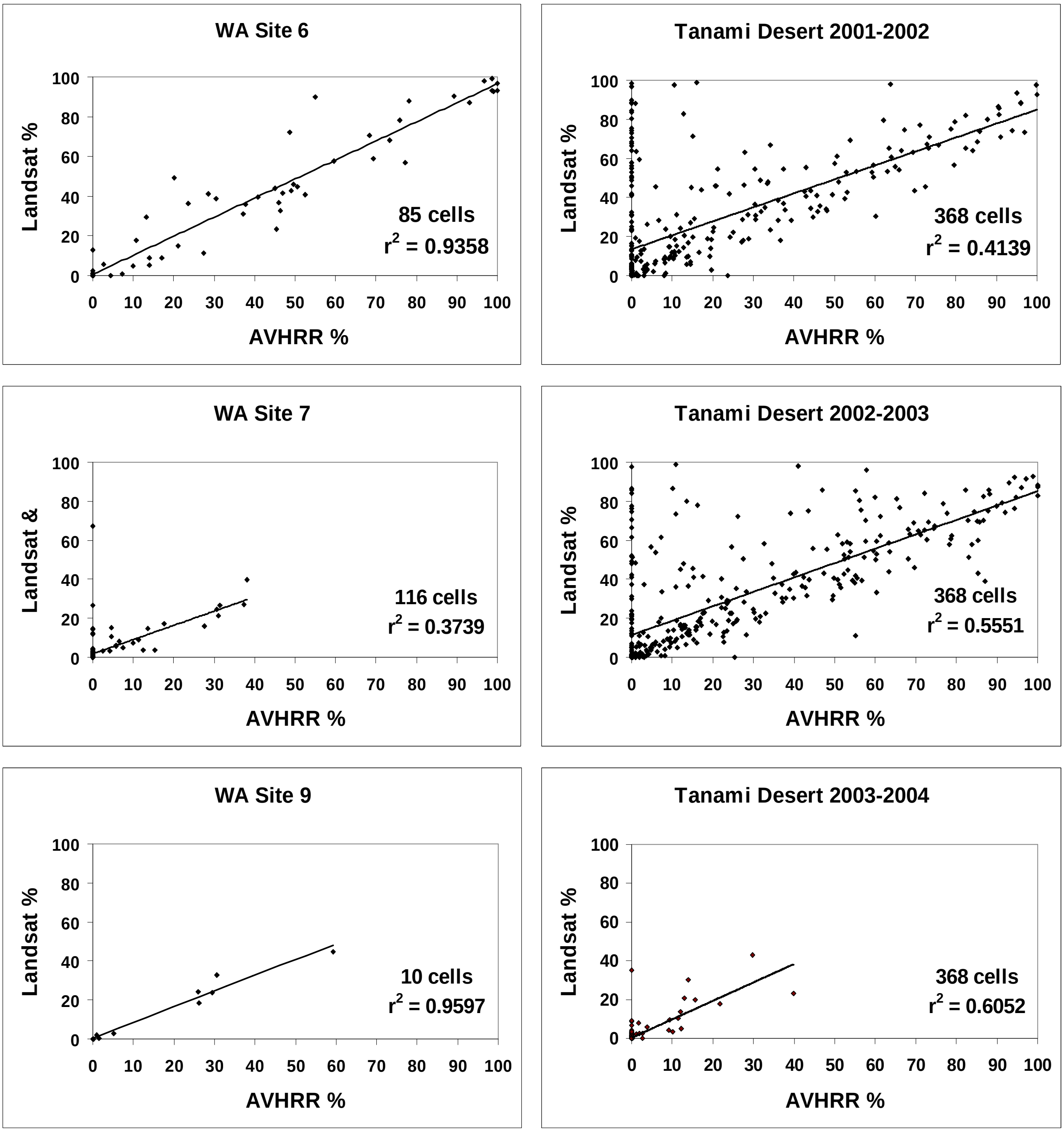


Figure 4.5 Western Australia and Tanami Desert - Estimates of the extent of burning as derived from AVHRR and Landsat imagery, for each 10 x 10 km grid cell

4.5 NOAA AVHRR fire hotspot mapping accuracy assessment

Active fires locations (fire hotspots (FHS)) are now reported routinely in Australia from daily NOAA satellite evening overpasses (Justice et al., 2003; Landgate, 2008a). Automated procedures are used to geometrically and radiometrically correct the raw AVHRR data. The locations of active fires are then generated through an automated process based on a contextual algorithm by Lee and Tag (1990) which measures individual pixels that are hotter than their surrounds. The algorithm compares the temperature of individual pixels in band 3 (the mid thermal infrared waveband where maximum thermal emissions occur at flame temperature), to temperatures from the surrounding pixels in band 5 (the thermal infrared wavelength where maximum thermal emissions occur at ambient land temperatures) (Craig et al., 2002; Smith et al., 2007b). Thresholds of the algorithm are adjusted for Australian conditions latitudinally. Pixels are classified as definite hotspots if they satisfy all four temperature threshold tests, and as “Possible FHS” if they satisfy three out of the four criteria (Craig et al., 2002).

4.5.1 Methodology

4.5.1.1 Pre-processing

The AVHRR hotspot data were supplied by Landgate (Western Australian Land Information Authority) as point datasets for the entire country, from 1998 to 2004 inclusive, and imported into the GIS.

For each of the 11 sites, a subset of the AVHRR fire hotspot dataset covering the same spatial and temporal extent as both the AVHRR and Landsat burnt area datasets was extracted. Hotspots from the preceding three months were also included if they matched a burnt area record. The data for South Australia were clipped to the border of the three parks and reserves.

The AVHRR fire hotspot dataset can contain more than one record for the same location and date. This may be because a hotspot was identified by different satellites on the day, or the same satellite on the next orbit. A small number of duplicates may also be attributed to the processing and projection of the data within the GIS system (Craig et al., 2002; Gill et al., 2002b). For our analysis, only one record per location per day was used.

4.5.1.2 Comparison with NOAA AVHRR and validation burnt area datasets

The hotspot data were compared to both the Landsat and AVHRR burnt area datasets within the GIS. As in the State of Environment reporting (Craig et al., 2002; Gill et al., 2002b), any hotspots that were contained in a burnt area that was up to three months after the date of the hotspot record, were marked as having a match.

It has been estimated that there can be a mismatch between the real location of a hotspot, with that declared on the processed image, of as much as 3 km, and often of about 1 km (one AVHRR pixel) (Gill et al., 2002b). Comparisons with the burnt area datasets were therefore also performed with hotspots buffered by 1 km, to take into account the possibility of location accuracy errors of one pixel, due to the geo-positional swing of the satellite over its nine day repeat orbit cycle (Craig et al., 2002).

The hotspots records were flagged if they matched an AVHRR burnt area record or a burnt area record from the Landsat validation dataset. They were also flagged if they were within a 1 km buffer of either of them. The discussion below concentrates on the results from buffering the hotspots. The Uluru region is not included in this analysis because most of the burnt area data does not contain dates, making it impossible to calculate if hotspots are within three months or not. The relationship between the hotspots and the two burnt area databases for each validation site is presented in tables 4.4 and 4.5 and figures 4.6-4.8.

4.5.2 Results

Overall, over 52% of all hotspots fell directly within both a Landsat and AVHRR burnt area record that was mapped within three months of the hotspot data (table 4.4 and figures 4.6-4.8). Almost 75% were within 1 km of both, 16.5% fell within 1 km of a related Landsat burnt areas only, less than 2% within 1 km of related AVHRR burnt areas only. Only 7.5% were more than 1 km from either, and many of these were no more than a few kms from one or other burnt area dataset.

There were 14 981 hotspots in total, mapped at 1 km intervals. Of these, 13 587 were within 1 km of a related Landsat burnt area (totalling 51 444 km^2), and 11 386 were within 1 km of a related AVHRR burnt area (totalling 38 894 km^2) (table 4.5 and figures 4.6-4.8). This means, that overall, over 73% of Landsat and 70 % of AVHRR mapped burnt area had no temporally related hotspots within 1 km. This occurred in both large and small burnt area patches.

In Western Australia (table 4.4 and figure 4.6), over 82% of site 6 and almost 90% of site 9 hotspots fell within 1 km of both burnt area datasets. A small cluster (~20 hotspots) in the east of site 6 is unmapped in either burnt area dataset. In site 7 almost one third of the hotspots had no matching burnt area record. The majority of these (15/22) occurred in a patch to the south of the other fires. At site 7, the fires were quite fragmented and only 11% of the burnt area had an associated hotspot (table 4.5 and figure 4.6). Site 9 had 42% of the burnt area represented by hotspots also, one of the best results.

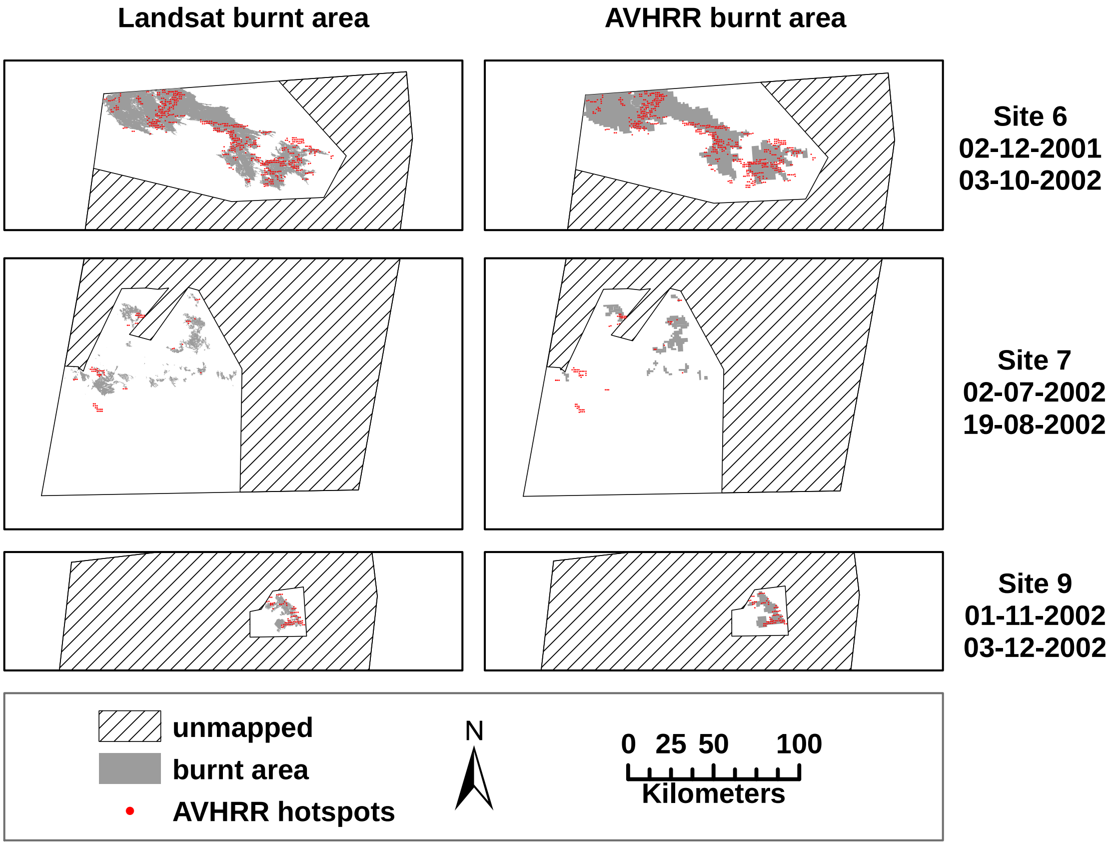


Figure 4.6 Western Australia - AVHRR hotspots in Landsat and AVHRR burnt areas

The Tanami Desert validation site had 5 643 hotspots over the three year period. There was a lot of similarity in the percentages between the three years, despite the fact that there was far less fire in the third year (table 4.4 and figure 4.7). Overall, 77.8% of all the buffered hotspots intersect both the Landsat and AVHRR burnt areas. Only 4% are not associated with any burnt area. Of the remainder, the vast majority (17%) fall within Landsat burnt areas only, particularly the large patches not mapped from AVHRR in the first two years. Just over 1% of hotpots fall only within AVHRR burnt areas (some, but not all, AVHRR-only burnt patches have at least one associated hotspot). In the first two years, approximately 70% of the burnt areas had no corresponding hotspots. This was only 54% for AVHRR and 63% for Landsat in the third year, where most of these smaller fires were captured by the hotspot data (table 4.5 and figure 4.7).

Over 2 000 hotspots were recorded in the Davenports scene. Here, 83% of all the buffered hotspots intersect both the Landsat and AVHRR burnt areas, and very few are associated with an AVHRR burnt area record only (table 4.4 and figure 4.7). There are no hotspots more than a few kms from one of the burnt area dataset. Once again, over 70% of both burnt area datasets had no matching hotspot records (table 4.5 and figure 4.7).

Table 4.4 AVHRR Hotspots in Landsat and AVHRR burnt areas

			% of hotspots in burnt area datasets				% within 1 km of burnt area datasets			
Validation site	Approx. dates	# Hotspots	In both	Landsat only	AVHRR only	In neither	In both	Landsat only	AVHRR only	In neither
				WESTERN AUSTRALIA						
WA site 6	12/01	595	65.0	12.3	8.7	13.9	82.4	11.3	1.7	4.7
WA site 7	07-08/02	73	12.3	21.9	4.1	61.6	27.4	42.5	0.0	30.1
WA site 9	11-12/02	68	50.0	8.8	17.6	23.5	89.7	2.9	1.5	5.9
WA total		736	58.4	12.9	9.1	19.6	77.6	13.6	1.5	7.3
				NORTHERN TERRITORY						
Tanami	2001-2002	2 114	54.7	16.2	9.8	19.3	75.3	18.0	1.5	5.3
	2002-2003	3 391	49.1	15.7	15.1	20.1	79.7	16.4	1.1	2.9
	2003-2004	138	27.5	10.9	21.0	40.6	68.1	18.1	0.7	13.0
	Total	5 643	50.7	15.8	13.3	20.3	77.8	17.0	1.2	4.0
Davenports	08-09/01	2 264	59.5	17.6	5.2	17.7	82.9	13.8	0.3	3.0
Coniston	2000	17	47.1	29.4	11.8	11.8	82.4	17.6	0.0	0.0
	2001	619	36.7	43.1	4.8	15.3	55.6	33.9	2.4	8.1
	2002	634	41.2	18.8	7.6	32.5	58.8	14.4	12.9	13.9
	2003	42	19.0	9.5	0.0	71.4	28.6	4.8	0.0	66.7
	2004	48	27.1	16.7	10.4	45.8	47.9	6.3	6.3	39.6
	Total	1 360	38.0	29.6	6.3	26.1	56.3	22.7	7.4	13.6
Erldunda	2002	2 191	57.1	18.4	3.1	21.4	71.6	12.9	1.2	14.3
NT total		11 458	52.1	18.3	8.9	20.7	75.0	16.3	1.8	6.9

Table 4.4 Continued

			% of hotspots in burnt area datasets				% within 1 km of burnt area datasets			
Validation site	Approx. dates	# Hotspots	In both	Landsat only	AVHRR only	In neither	In both	Landsat only	AVHRR only	In neither
					SOUTH AUSTRALIA					
Mamungari	2000-2001	233	41.2	22.3	6.0	30.5	55.4	18.0	2.1	24.5
	2001-2002	15	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
	2002-2003	2 104	60.8	19.6	7.1	12.5	84.8	12.6	0.8	1.8
	2003-2004	59	0.0	0.0	33.9	66.1	0.0	0.0	47.5	52.5
	Total	2 411	57.0	19.3	7.6	16.1	79.4	12.7	2.1	5.8
Yellabinna	1998-1999	12	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
	1999-2000	35	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
	2000-2001	216	0.0	79.6	0.0	20.4	0.0	88.4	0.0	11.6
	2001-2002	7	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
	2002-2003	8	0.0	12.5	0.0	87.5	0.0	25.0	0.0	75.0
	2003-2004	20	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
	Total	298	0.0	58.1	0.0	41.9	0.0	64.8	0.0	35.2
Ngarkat	1998-1999	62	33.9	8.1	9.7	48.4	56.5	6.5	8.1	29.0
	1999-2000	7	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0
	2000-2001	0	-	-	-	-	-	-	-	-
	2001-2002	0	-	-	-	-	-	-	-	-
	2002-2003	9	0.0	0.0	0.0	100.0	0.0	55.6	0.0	44.4
	2003-2004	0	-	-	-	-	-	-	-	-
	2004-2005	0	-	-	-	-	-	-	-	-
	Total	78	26.9	6.4	7.7	59.0	44.9	11.5	6.4	37.2
SA total		2 787	50.1	23.0	6.8	20.1	69.9	18.1	2.0	10.0
Grand total		14 981	52.1	18.9	8.5	20.5	74.2	16.5	1.8	7.5

Table 4.5 Landsat and AVHRR burnt areas without AVHRR Hotspots (buffered to 1 km)

(Excluding Uluru validation site)

Validation site	Approx. dates	# hotspots	Total burnt area km^2		Number of hotspots in		% burnt area without hotspots in	
			Landsat	AVHRR	Landsat	AVHRR	Landsat	AVHRR
			WESTERN AUSTRALIA					
WA site 6	12/01	595	2 141	2 174	557	500	74.0	77.0
WA site 7	07-08/02	73	445	318	51	20	88.5	93.7
WA site 9	11-12/02	68	149	180	63	62	57.7	65.6
WA total		736	2 735	2 672	671	582	75.5	78.2
			NORTHERN TERRITORY					
Tanami	2001-2002	2 114	9 115	5 751	1 972	1 623	78.4	71.8
	2002-2003	3 391	10 754	8 946	3 258	2 738	69.7	69.4
	2003-2004	138	321	206	119	95	62.9	53.9
	Total	5 643	20 190	14 903	5 349	4 456	73.5	70.1
Davenports	08-09/01	2 264	8 563	6 944	2 188	1 883	74.4	72.9
Coniston	2000	17	592	650	17	14	97.1	97.8
	2001	619	2 228	1 504	554	359	75.1	76.1
	2002	634	984	965	464	455	52.8	52.8
	2003	42	144	67	14	12	90.3	82.1
	2004	48	245	305	26	26	89.4	91.5
	Total	1 360	4 193	3 491	1 075	866	74.4	75.2
Erldunda	2002	2 191	5 609	4 654	1 851	1 595	67.0	65.7
NT total		11 458	38 555	29 992	10 463	8 800	72.9	70.7

Table 4.5 Continued

Validation site	Approx. dates	# hotspots	Total burnt area km^2 Landsat	Total burnt area km^2 AVHRR	Number of hotspots in Landsat	Number of hotspots in AVHRR	% burnt area without hotspots in Landsat	% burnt area without hotspots in AVHRR
SOUTH AUSTRALIA								
Mamungari	2000-2001	233	2 911	1 404	171	134	94.1	90.5
	2001-2002	15	0	12	0	0	-	100.0
	2002-2003	2 104	4 116	4 077	2 045	1 802	50.3	55.8
	2003-2004	59	0	67	0	28	-	58.2
	Total	2 411	7 027	5 560	2 216	1 964	68.5	64.7
Yellabinna	1998-1999	12	12	0	0	0	100.0	-
	1999-2000	35	0	0	0	0	-	-
	2000-2001	216	0	0	191	0	-	-
	2001-2002	7	1 866	0	0	0	100.0	-
	2002-2003	8	133	13	2	0	98.5	100.0
	2003-2004	20	87	0	0	0	100.0	-
	Total	298	2 098	13	193	0	90.8	100.0
Ngarkat	1998-1999	62	679	656	39	40	94.3	93.9
	1999-2000	7	1	0	0	0	100.0	-
	2000-2001	0	1	0	0	0	100.0	-
	2001-2002	0	38	1	0	0	100.0	100.0
	2002-2003	9	263	0	5	0	98.1	-
	2003-2004	0	3	0	0	0	100.0	-
	2004-2005	0	44	0	0	0	100.0	-
	Total	78	1 029	657	44	40	95.7	93.9
SA total		2 787	10 154	6 230	2 453	2 004	75.8	67.8
Grand total		14 981	51 444	38 894	13 587	11 386	73.6	70.7

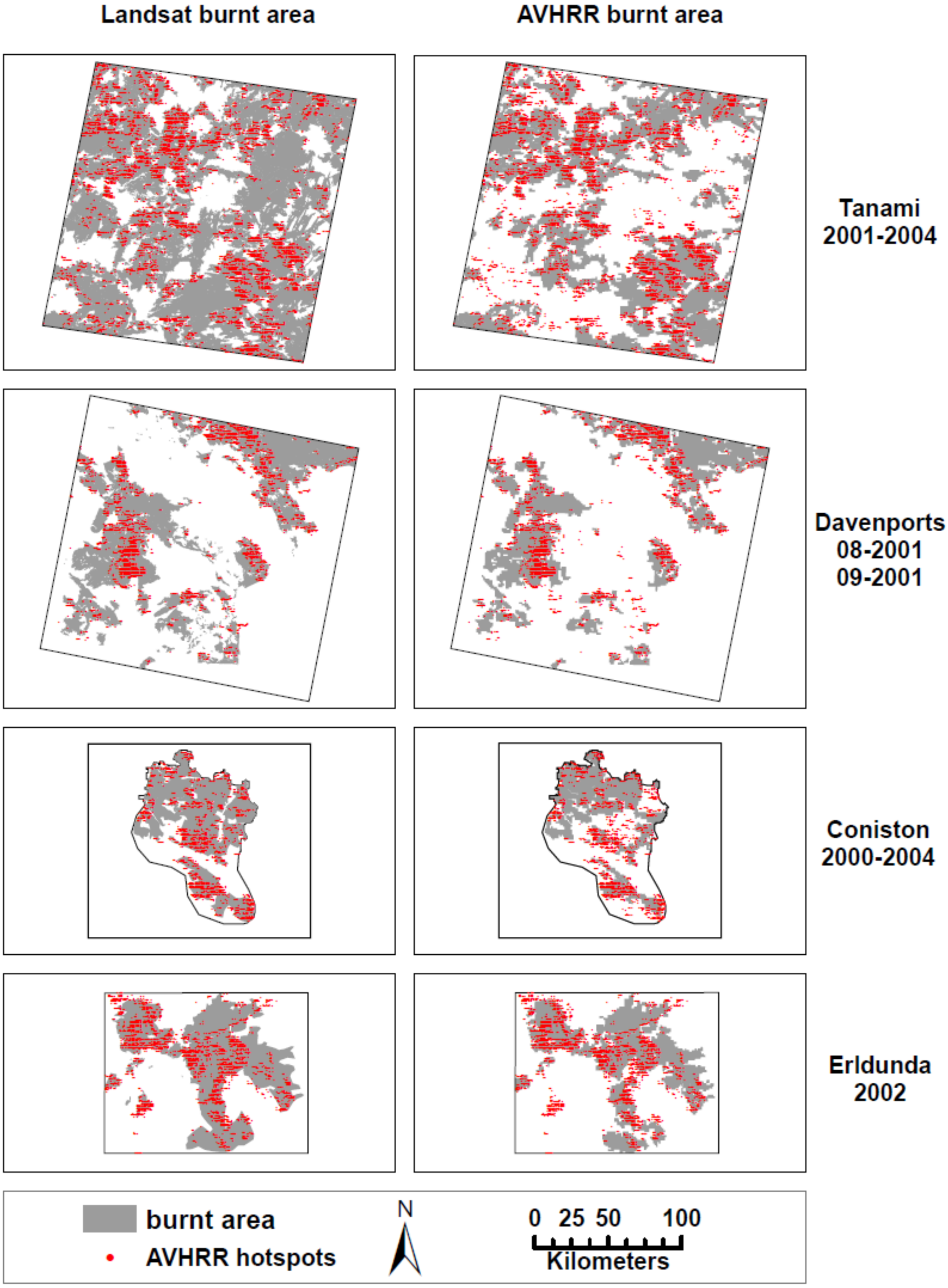


Figure 4.7 Northern Territory - AVHRR hotspots in Landsat and AVHRR burnt areas

There were 1 360 hotspots recorded in the Coniston area. There is a good fit between the hotspot data and both the Landsat and AVHRR burnt area datasets in 2000 (table 4.4 and figure 4.7). In 2001, approximately a third of the hotspots occur in the Landsat only burnt areas, while some scattered hotspots do not correspond to records in either burnt area database. In 2002 there is a cluster of 100 hotspots in the north, which have no corresponding Landsat burnt area record. Half of these do have a matching AVHRR burnt area record however. In 2003 and 2004 less area is burnt, and there are less matching hotspots (67% and 40% unmatched). Overall, 14% of hotspots that did not fall within either of the burnt area datasets. Once again, ~75% of both burnt area datasets had no matching hotspot records in total (table 4.5 and figure 4.7). This varied from 53% in 2002 to 97% in 2000.

Erldunda showed a pattern very close to the overall totals with almost 72% of hotspots within 1 km of both the validation and AVHRR burnt area datasets (table 4.4 and figure 4.7). The level of hotspots outside either was higher than the overall average though at 14%. Here, over 66% of both burnt area datasets had no matching hotspot records (table 4.5 and figure 4.7).

The totals for all South Australian Parks and Reserves are heavily influenced by the large proportion of these hotspots that were in Mumungari Conservation Park, particularly in the 2002-2003 season (table 4.4 and figure 4.8). In 2000-01 at Mumungari, there are hotspots associated with all mapped burnt areas, and a couple of clusters (each over 20 hotspots) not associated with any burnt area. The 15 hotspots (including a cluster of 10) in 2001-02 do not correspond to the small AVHRR-only burnt area. During 2002-03 85% of hotspots were mapped in both burnt area datasets. No hotspots were associated with a number of fairly large AVHRR-only burnt areas (see results section 4.2.1 and discussion section 7). Almost half of the 2003-04 hotpots are associated with the one AVHRR-only burnt area. Apart from 2002-03, when almost 50% of Landsat and 45% of AVHRR burnt area datasets had matching hotspot records, (the best match of any scenes), the hotspot data gives little indication of the extent of the burnt areas (table 4.5 and figure 4.8).

In Yellabinna, none of the 298 hotspots fell within the one small AVHRR burnt area. In total almost 65% were within 1 km of Landsat records (88% in 2000-02, and 25% in 2002-03). The 105 unmatched hotspots are scattered in groups of one to four fairly evenly throughout the study area. Overall 90% of Landsat burnt area and 100% of AVHRR burn areas had no matching hotspots (table 4.5 and figure 4.8).

Only 78 hotspots were recorded at Ngarkat Conservation Park, the majority in the first year, and four years recording none. In total, nearly 45% of there were related to records in both burnt area datasets, and almost 37% to neither. In 1998-99 over 94% of both burnt area datasets had no matching hotspots. Apart from this matched, 2% of the Landsat burnt area had matching hotspots in 2002-03 (table 4.5 and figure 4.8).

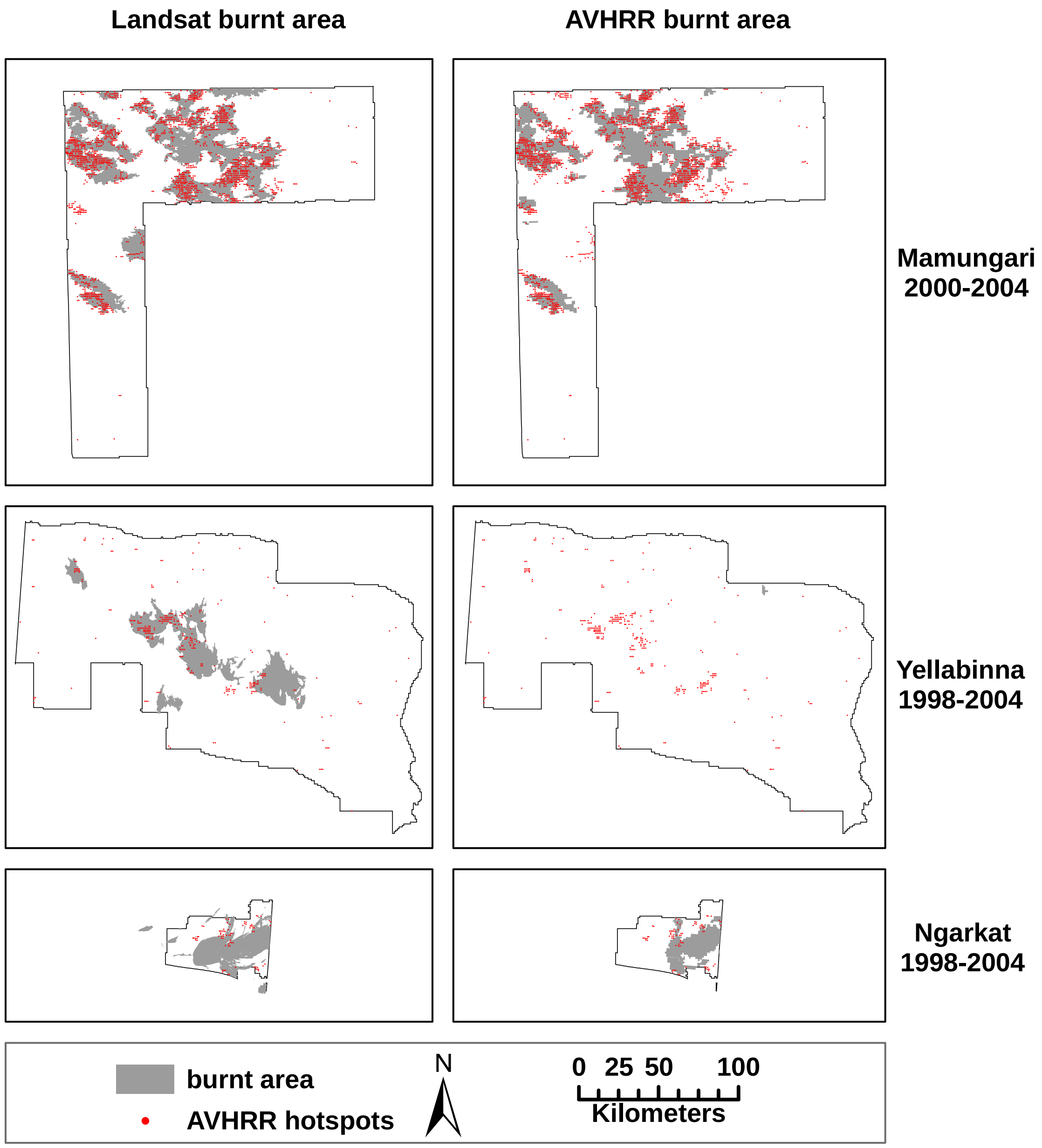


Figure 4.8 South Australia - AVHRR hotspots in Landsat and AVHRR burnt areas

4.6 Soil, vegetation, landuse and tenure

A visual examination of the burnt area data (both AVHRR and Landsat) was undertaken to examine if trends could be detected as to which areas burnt with relation to soil or vegetation type, land use or tenure (as defined in the digital atlas of Australian soils (Bureau of Rural Science, 1991), the national vegetation information systems (National Land and Water Resources Audit, 2001) (see figure 4.1), and the land use and tenure of Australia (Stewart et al., 2001) digital datasets). The burnt area mapped from Landsat but not AVHRR; and in particularly the larger distinct patches; were also examined to determine if soil or vegetation type influenced these errors of omission.

In Western Australia's site 6, the burnt area was confined to sands, with the fire scar stopping at the junction with loams. Vegetation, landuse and tenure are almost uniform in this site. At site 7 the area burnt was on Aboriginal reserve land, predominantly in the acacia forests and woodlands, on the massive and structured earths. The reverse was true for site 9, with fire mostly confined to the hummock grasslands on loams and massive and structured earths, and little crossing over into the acacia forests and woodlands on the red duplex soils in the northwest. Fire burnt on both the private leasehold and vacant crown land.

In the Northern Territory, fire at all validation sites (the Tanami Desert, Davenports, Uluru, Coniston Station, and Erldunda Station) affected all vegetation and soil types, landuse and tenures present. The same can generally be said of the three South Australian validation sites, Mamungari, Yellabinna and Ngarkat.

At Western Australia's site 7, the largest patch (106 km^2) of burnt area mapped from Landsat, but not AVHRR, was in the hummock grasslands on sands. A cluster of 15 hotspots without a matching burnt area was also in the hummock grasslands. There were other small (each < 10 km^2) fragmented areas of burnt area mapped only from Landsat in the acacia forests and woodlands and acacia shrublands on massive and structured earths.

In the Northern Territory, at least some burnt area mapped from Landsat, but not AVHRR, occurred on all vegetation and soil types, landuse and tenures present at each site. In the Tanami, 8 856 km^2 of Landsat burnt area was not detected in the AVHRR imagery. Much of this was composed of large patches from the first two years. This site is composed almost entirely of hummock grasslands. These patches undetected from the AVHRR imagery occur predominantly on the sands, but do cross over into the area of massive and structured earths in the east. While there is a greater mixture of vegetation and soil types in the Davenport site, the majority of undetected AVHRR patches also occur in the hummock grasslands on sands. The Uluru site is predominantly hummock grasslands on sands. The vast majority of undetected AVHRR burnt area, including one large patch (128 km^2) in the pre-2002 data, occurs here. At both Coniston and Erldunda, Landsat-only burnt areas (1 501 km^2 and 1 231 km^2) are spread fairly evenly over the different vegetation and soil types (see section 2.2), but the Landsat mapping is at a much generalized level.

At Mamungari, Yellabinna and Ngarkat in South Australia, at least some burnt area mapped from Landsat imagery only, occurred on all vegetation and soil types, landuse and tenures present at each site. At Mamungari five main patches account for the almost 3 000 km^2, spread evenly over the variety of vegetation types, but predominantly on the sands. For Yellabinna, the entire Landsat burnt area (half a dozen patches totalling almost 2 000 km^2), is unmapped in the AVHRR burnt area dataset at Yellabinna. They are all on the mallee woodlands and shrublands on sands, which dominate the area. In Ngarkat, the burnt areas not mapped from AVHRR (over 450 km^2, mostly in one patch) occur in the heath in the west, with essentially none in the mallee woodlands and shrublands in the east.

4.7 Discussion

This paper has assessed the accuracy of AVHRR-based fire hotspots (FHS) and fire affected area (FAA) datasets at 11 sites in arid and semi-arid Australia (1998-2004), including a period of unusually high rainfall in some areas, for the first time. We examined if years, or areas, of high fire result in better detection rates. We also examined if soil or vegetation type, landuse or tenure affect the area burnt, or if differences in soil or vegetation type can account for errors of omission. Issues particular to mapping fire in arid and semi-arid environments are discussed below.

In summary, it can be seen that mapping accuracy of burnt areas from AVHRR imagery can be highly variable between areas, and from year to year within the same area. Where there are corresponding patches in the AVHRR and Landsat datasets, the fit is good. However, the AVHRR dataset misses some large patches (errors of omission). Other AVHRR-based patches appear to have been mapped twice at different times, becoming evident amongst the errors of commission. Most hotspot records have a corresponding burnt area record in the AVHRR and/or Landsat datasets, but with fewer matches in areas of smaller fires. The hotspots alone, however, do not give a good indication of the area burnt, as many go undetected.

The comparison of AVHRR- versus Landsat-based burnt area estimates was variable from 0% to 94%. Regressions were also variable, with r^2 values ranging from 0.37 (n=116) to 0.94 (n=85) in Western Australia, and 0.41 to 0.61 (n=368) in the Tanami. The high variability in burnt area mapping accuracy is consistent with the findings of Yates and Russell-Smith (2002) with r^2 ranging from 0.41 to 0.81, and Collett et al. (2001) in northern Australia, who found that NOAA pixels only started to be detectable as burnt when quite a high percentage (over 50%) of the given pixel was burnt.

However, the interpretation of results from this exercise is not straightforward. One should be careful when comparing results from scenes with large total burnt areas and those with small total burnt areas. The scenes and years where large areas were burnt, had smaller omission and commission error percentages (apart from Yellabinna), but these errors can be relatively large patches in area. Similarly, care should be taken when comparing results from different size validation sites. Site 7 in Western Australia and the Tanami in 2003-04 had comparable burnt areas, and omission and commission error percentages; but the r^2 values differed greatly (0.37 (n= 116) and 0.60 (n=368)). Also, the 2003-04 Tanami data had the worst errors of omission and commission for the site, but the best regression results. This exercise has showed the importance of using a number of different techniques for measuring and interpreting the accuracy of the datasets.

For validation sites where there was more than one year of data, years with small areas burnt had very different results to high fire years, but made little difference to the overall totals for that scene. This shows the importance of carrying out validation exercises in these environments for both the usual low fire years, as well as the uncommon high fire years, and reporting them separately.

In general though, it can be said that, where there is an overlap between AVHRR and Landsat burnt areas, that the fit is generally quite good. Minor differences are mostly due to the difference in scale between the two datasets. The finer detail is captured by Landsat, while AVHRR over or under-estimates along some edges and over-estimates in fragmented patches. AVHRR is unable to detect fires less than 1 km^2 and often less than 4 km^2, as Craig (2002) and Yates and Russell-Smith (2002) found. This is very evident in the early Uluru data. Minor differences may also be due to data orbital characteristics, or rectification and other pre-processing issues (Yates and Russell-Smith, 2002).

However, the AVHRR dataset occasionally misses large patches that are mapped from Landsat imagery. It is interesting that, in many instances, AVHRR hotspots were recorded in these areas for the appropriate dates (see figures 4.6-4.8). This adds weight to the accuracy of the Landsat data.

There are many factors which may contribute to these errors of omission. Some are common to all remote sensing. For example, atmospheric conditions such as smoke, haze or cloud may obscure the ground for some time following a fire (Justice et al., 2003; Yates and Russell-Smith, 2002), as was evident in some of the Landsat Quicklook images around the time of some fires (see section 4.2.1 above). Other issues are more specifically related to conditions in arid and semi-arid environments, as discussed below.

Overall, visual investigation highlighted no clear relationships between soil, vegetation, landuse or tenure, and burnt area in general. Fire affected all vegetation and soil types, landuse and tenures present at each validation site. Similarly, at least some errors of omission occurred on all vegetation and soil types, landuse and tenures present at each site. However, the majority of the omission patches occurred in hummock grasslands on sands, apart from in South Australia. This is at least partly because this vegetation and soil type dominate the validation sites.

Generally, actively growing vegetation has very high reflectance values in the near infra red (NIR) range (AVHRR band 2). The spectral signature of hummock grasslands is distinct from the signature of greener vegetation. Reflectance in the visible green wavelength is lower than usual, while high reflectance in the red band and a lower peak in the near infrared are associated with the exposed soil. The spectral signature of hummock grasslands approaches that of greener vegetation, dependent on the amount of recent rainfall (Allan, 1993b).

In other environments, burnt areas usually appear darker than the surrounding vegetation due to a deposit of surface charcoal, or the exposure of dark soil. However, the sandy desert soils in arid and semi-arid Australia are brighter in the NIR than the vegetation in many cases. Immediately following fire there may be very low reflectance in all bands due to dark ash lying on the ground. But the burnt char may be quickly blown away changing the signal from dark to bright in all bands compared with the surrounding vegetation (Allan, 1993b; Craig et al., 2002; Justice et al., 2003). Smith et al. (1998) noted that, in the Northern Territory, the characteristic of high reflectance in hummock grassland fire scars was unique to the sparsely vegetated ground south of 21°S, whilst fire scars north of latitude 21°S displayed low reflectance in all channels. This reversal was attributed to the relatively low production of ash in arid grasslands leaving bare soil exposed, as compared to the greater coverage of ash produced by a fire in the more densely vegetated regions north of 21°S. This ties in with the findings of Turner et al. (2008) (Chapter 5), who demonstrated that the main trends in fire distribution and area burnt in arid and semi-arid Australia follow latitudinal rainfall gradients. Turner et al. (2008; 2009b) (Chapters 5 and 6) also used regression analysis to show the positive relationship between area burnt and the amount of antecedent rainfall (particularly above average) in these environments.

As the burnt area mapping is a semi-manual process, operational experience and human error must be taken into account (Yates and Russell-Smith, 2002). Operators must be aware of the particular conditions in arid and semi-arid environments described above, and how the spectral signature of both the vegetation and fire scars reflect these, and how they can both potentially change from one year to the next for a given area, particularly in years following unusually high rainfall and the associated extra biomass.

Many fires in arid and semi-arid Australia are of low intensity, or in areas of sparse discontinuous fuel, which leave little imprint on the landscape that can be detected by the current semi-automatic mapping process employed by Landgate (Western Australian Land Information Authority). Hummock grasses grow, following rainfall events, in an increasingly large, round ‘hummock’ that extends outward, whilst dying in the centre, forming a ring. The hummock can reach up to 30 cm in height and a metre in diameter (Specht and Specht, 1999). Plants are well spaced and have a foliage cover generally within the 10-30% range (AUSLIG, 1990). Post-rainfall ephemeral growth can provide fuel to transport fire across the normally bare ground between hummocks. Similarly, fuel accumulation is slow in the mallee and heath and vegetation of South Australia because of low fertility and lack of rainfall. Mallee has a foliage cover of 10-30%, and heath 30-70% (AUSLIG, 1990). Collett et al. (2001) found that an AVHRR pixel only started to be detectable as burnt when quite a high percentage (> 50%) of the given pixel was burnt. This perhaps explains the total lack of AVHRR-detected burnt patches in the sparsely vegetated mallee woodlands and shrublands on the sands of Yellabinna in South Australia, and the heath of Ngarkat.

Also , in areas of sparse vegetation, the spectral reflectance changes from fire are often short lived and may only last a few days (Smith et al., 2007b). These factors can make it difficult to detect changes, particularly if they are obscured for any length of time. More research needs to be carried out on mapping accuracy in both mallee and heath to investigate these omission errors. Perhaps data from Project FuSE, which is aiming to describe fuel dynamics and fire behaviour in mallee and heath, could be used to further such research.

There are also a few burnt areas which have been mapped from the AVHRR imagery but not from Landsat (commission errors), particularly in the Tanami, Uluru, Coniston and Mamungari scenes. At least some of these errors of commission may be due to human error. This was seen in the AVHRR data in the southeast corner of the Tanami Desert validation site, where a burnt area was inadvertently mapped twice in different years (see results section 4.2.1). A 120 km^2 AVHRR patch from May 2002 is identical, bar a couple of pixels, to another AVHRR patch mapped in December 2001 (118 km^2). The 2001 patch overlaps a Landsat patch mapped in January 2002 and has one associated hotspot. It seems probable that the later AVHRR patch was mapped a second time in error, as it is extremely unlikely that two identical areas would burn, especially so close in time. Similarly, at Mamungari, all the 2000-01 AVHRR burnt area patches totaling ~600 km^2, (each with associated Landsat burnt patches and 145 matching AVHRR hotspots), are very similar in shape to 2002-03 AVHRR burnt areas that have no associated Landsat burnt patches or AVHRR hotspots (see results sections 4.2.1 and 5.2). The earlier patches remain visible on the Landsat Quicklooks right up to the 2002-03 season. From the Quicklooks, the other 2002-2003 commission errors appear to be other old fire scars also still visible. These 2002-03 patches would appear therefore to also be a mapping error.

While it is impossible to validate the hotspot dataset retrospectively, indications from comparing it to both the Landsat and AVHRR burnt area datasets are that the spatial accuracy is generally reasonably good. Overall, only 7.5% of hotspots buffered to 1 km do not correspond to a burnt area in either of these datasets mapped in the following three months, but this ranged from 0% to 100% at different sites. Hotspots are somewhat better correlated with the Landsat data, reflecting the fact that some large patches of burnt area were not detected in the AVHRR imagery. There is generally poor correlation between hotspot and burnt area records in areas of low fire activity due to the limited number of fires and small areas mapped as burnt. The chances of a satellite picking up one of these small fires while it is actually burning are obviously smaller. Craig et al. (2002) reported similar results for the arid zone in the State of Environment report. They found a high correlation between hotspots and burnt area from August to October 1999, the time of greatest fire activity, where 70% to 80% of hotspots fell within a temporally related burnt area, but little correlation in times of low fire activity.

As with the burnt area data, minor locational errors may be due to data orbital characteristics, or rectification and other pre-processing issues (Yates and Russell-Smith, 2002). A much higher "hit rate" is achieved when a 1 km buffer is applied when attempting to match hotspots to burnt area data.

One of the major problems with hotspot detection in inland Australia is that the high surface reflectance of the soils and high temperatures cause saturation of channel 3 or significant errors of commission, limiting use of data from daytime orbits (Craig et al., 2002; Justice et al., 2003). Other orbits may miss the period of peak fire intensity, which usually occurs in the day, and then have insufficient radiance to be detected. Many fires may last less than twenty-four hours and are missed due to the timing of the overpass. They may also be obscured by cloud, smoke or haze, or affected by low sun angle or rough topography (Craig et al., 2002; Gill et al., 2002b; Justice et al., 2003; Yates and Russell-Smith, 2002).

It can be seen that hotspots alone do not give a good indication of the size of the burnt area (Craig et al., 2002), and severely underestimate it, as Gill et al. (2002b) found in the southwestern Australian forests also.

While the NOAA AVHRR satellite sensor is suited to map and monitor fire activity on a daily basis at a continental scale (Craig et al., 2002) it is unusable for local mapping of ecologically sensitive areas (Justice et al., 2003), especially where knowing the level of fragmentation in a burnt area is important. Although far from perfect, the mapping of hotspots and burnt area from AVHRR imagery has provided valuable information on fire regimes in arid and semi-arid Australia, where little was known a decade ago (Chapter 5, see also Turner et al., 2008).

While this study has given a broad view of the reliability of the NOAA AVHRR fire products in arid and semi-arid Australia, a more rigorous validation exercise should be embarked upon. High resolution validation data should be specifically prepared and accompanied by detailed ground verification exercises (using vehicle or on-ground measurements and aerial transects), preferably at the time of overpasses from the high resolution imagery. This was unfortunately not possible within the timeframe or budget of this analysis.

Chapter 5

AN INTRODUCTION TO PATTERNS OF FIRE
IN
ARID AND SEMI-ARID AUSTRALIA
1998-2004

Abstract

Fire is a crucial element in shaping our world, whether caused naturally by lightning or by humans, either accidentally or on purpose. These fires can have both positive and negative consequences and impacts on our natural environment, society and its economics, not to mention global climate.

Previous analyses of fire regimes in arid and semi-arid Australia have been of limited spatial and/or temporal extent. This lack of knowledge has hampered attempts at effective management. Satellite imagery allows the continuous detection, monitoring and mapping of fires. Active fires can be detected as fire hotspots, and burned areas mapped as patches from the change of surface reflectance properties in successive images. Data from NOAA's Advanced Very High Resolution Radiometer (AVHRR) were used to assess the distribution, seasonality, frequency, number and extent of fire hotspots (FHS) and fire affected areas (FAA) across the entire arid and semi-arid country of Australia from 1998 to 2004.

Utilising both fire datasets is important, as they complement each other and provide a more robust analysis of fire patterns. Between 1998 and 2004 almost 27% of arid and semi-arid Australia burnt at least once. The main trends in fire distribution follow latitudinal rainfall gradients. Regression analysis also shows a strong relationship with the pattern of antecedent rainfall. The seasonality of fire events varies between climate zones in accordance with the varying distribution of precipitation and temperature, which influence fuel accumulation and curing.

For the first time we have a picture of fire patterns across the entire arid and semi-arid regions of the country. This includes a number of high fire years in certain areas following above-average rainfall. This analysis highlights similarities and differences between regions, giving policy makers and managers a basis from which to make more informed decisions in the present, and with which to compare future regimes.

5.1 Introduction

Fire is generally not associated with arid or semi-arid landscapes by the general public, but can frequently exceed 10,000 km² (one million hectares), especially following high rainfall events (Allan and Southgate, 2002). Management of fires in arid and semi-arid lands has varied over the centuries in its emphasis, from "fire-stick farming" and hunting in traditional Aboriginal economies (Bird et al., 2005; Bowman, 1998; Burrows et al., 2006a; Fensham, 1997), to suppression throughout most of the 1900s (Griffin et al., 1983; Hodgkinson et al., 1984). In the last few decades, prescribed burning has been used as a management option for fuel reduction (Craig, 1999; Uluru-Kata Tjuta Board of Management and Parks Australia, 2000), pastoral land management (Craig, 1999; Letnic, 2004; Myers et al., 2004; Vitelli and Pitt, 2006) and biodiversity conservation (Gill et al., 2002a; Gunawardene and Majer, 2005; Keith et al., 2002), but all to a somewhat limited extent (Edwards et al., 2008).

We now realise that we must attempt to balance all the elements. While using fire to our advantage and preventing it from causing damage to our property or ourselves, we must also strive to maintain the balance of our ecosystems and climate, and recognise fire's cultural significance to Aboriginal communities. As far back as 1995 Morton et al. advocated a new approach to the overall management of arid and semi-arid Australia through the integration of conservation and production. A holistic adaptive management approach has gained ground more recently (Altman and Whitehead, 2003; Benson, 2001; Ellis et al., 2004; Gill et al., 2002a). In theory, current legislation in Australia tries to take all aspects into account. In reality however, attempts at effective management are being hampered by the lack of explicit regulations or guidelines for measuring and managing fire regimes in the dry climate zones (Craig, 1999; Hodgkinson, 2002; Noble and Grice, 2002; Woinarski and Fisher, 2003).

The Desert Knowledge Cooperative Research Centre is a national research network, linking Indigenous and local knowledge with science and education, to improve desert livelihoods. Project 'Desert Fire', of which this research forms a part, is fundamental to the principles of the DK CRC. The goal of Desert Fire is to "adapt and maintain appropriate fire regimes and their management based on robust research, planning, review and communication to support the diverse users and managers of desert lands to achieve a balance of their ecological, social and economic priorities".

One of the first steps in defining "appropriate" fire regimes is to establish what regimes are currently operating across arid and semi-arid Australia. Early aerial photography and Landsat satellite images have been used to provide information on fire extent and occurrence for many years (Allan and Southgate, 2002). These studies have had a regional focus (the Western Desert (Burrows and Christensen, 1991); Central Australia (Allan, 1993a; Edwards et al., 2008); the Great Victoria Desert (Curry, 1996; Haydon et al., 2000); the Tanami Desert (Kaethner, 2004; Southgate et al., 2006)), and have been unable to provide a complete picture of the spatial and temporal patterns (fire regimes) of fire in the dry climate zones.

Data from NOAA's Advanced Very High Resolution Radiometer (AVHRR) have been used operationally for bushfire management in the NT since the mid 1980s, although there is little reference to this in the scientific literature (Allan and Willson, 1995; Craig et al., 1995; Justice et al., 2003). Fire Affected Areas (FAA) are digitised from changes in NOAA-AVHRR satellite images over the nine day orbital cycle, and daily fire hotspots (FHS) from AVHRR channel 3 (3.75 μm) (Craig et al., 2002). It was not until recently that the Western Australian Department of Land Information (DLI) compiled both datasets for the entire Australian continent dating back to 1998.

By definition, the hotspot database (FHS) is an underestimation of the occurrence of fire, as it can only possibly detect active fires at the time of the satellite overpass. The Fire Affected Area (FAA) database is also an underestimation, as patches less than 4 km² are normally not detectable (Craig et al., 2002). These two datasets are complimentary, and both are required to provide a more complete perspective on the occurrence of fire, especially in areas where fires of small area are common.

The only major study on fire regimes to utilise both datasets was commissioned as part of the Australian Government's 2001 State of the Environment report (Craig et al., 2002). It analyses the distribution, density, extent and seasonality of fires in Australia, for a two year period (from April 1998 to March 2000), with little detail on desert areas. Other papers in this series include those by Williams (2002a) on mulga systems, and Russell-Smith (2002) on savanna country. Analysis using the FAA data has also been carried out in the Australian savannas by Craig (1999), Russell-Smith et al. (2003b), and Spessa et al. (2005).

Using statistical analysis on both the FAA and FHS data within a GIS framework, this paper objectively describes the broad patterns of fire distribution, seasonality, frequency, number and extent, in arid and semi-arid Australia as a whole for the first time. It also looks at regional variations, to highlight similarities and differences in fire regime between climate zones. While the data do not cover an extended timeframe (1998 to 2004), they are important because they include a number of years of above-average rainfall and associated fires in some regions.

Arid and semi-arid Australia is a vast area with limited access and resources for fire management. This includes a sparse road network and inaccessible terrain, as well as a lack of knowledge, management strategies, manpower, time, equipment, skills and funding (Edwards et al., 2008; Myers et al., 2004). Our analysis may help identify those areas where management efforts can be most useful, and provide a baseline from which to compare results in an adaptive management framework.

5.2 Study Area

Our study area is delineated by the Australian Bureau of Meteorology’s “dry climate” zones, which uses a modification of Köppen’s classification of world climates. These zones are defined on the basis of there being an excess of evaporation over precipitation, which is determined from the mean annual temperature and the mean annual rainfall over 30 years (Stern et al., 2000). They consist of two main groups, desert and grassland, which are further subdivided based upon differences in the seasonal distribution of temperature and precipitation (figure 5.1).

NOTE:
This figure is included on page 135 of the print copy of the thesis held in the University of Adelaide Library.

Figure 5.1 Australian dry climate zones

Based on Stein et al. (2000)

These arid and semi-arid lands, often referred to as rangelands, cover 70% of Australia (5.5 million km²) and are inhabited by only 2% of the population (over 500,000 people) (Brown et al., 2008). Median annual rainfall ranges from about 250 mm in the south, up to 800 mm in the north and 500 mm in the east. This rainfall is highly variable, with extremes of long dry periods and flooding deluges (BOM, 2005). Soils are characteristically very infertile over extensive areas (BRS, 1991), and the vegetation is mainly spinifex hummock grasslands, acacia woodlands and scrublands, and tussock grasslands (National Land and Water Resources Audit, 2001). The landscape and vegetation of the arid lands have a strong influence on land use and productivity.

Pastoral lands account for about 50% of arid and semi-arid Australia (Stewart et al., 2001), producing mostly cattle in the north and sheep in the south. They have a diverse range of vegetation including grassy plains, open woodlands with a mix of grasses and acacias (mostly mulga), and some areas of acacia woodlands with minimal understoreys (National Land and Water Resources Audit, 2001). Grazing by animals, including termites, generally keeps the fuel loads low, except after extended periods of widespread rain when growth can far exceed consumption (Hodgkinson, 2002).

Aboriginal lands currently comprise about 20% of the study area with the majority in the NT, while most vacant crown land is in WA and amounts to a further 15% (Stewart et al., 2001). Together, they roughly equate to the spinifex-covered sandplains and dunefields and stony deserts which are too unproductive and variable for livestock, but are home to a rich termite and lizard fauna (BRS, 1991; National Land and Water Resources Audit, 2001). Aboriginal communities largely exist by subsistence activities, some small business enterprises such as painting and bush-tucker, and government payments, but pastoralism is practiced in some areas. Spinifex grasses are very flammable and these grasslands are most regularly and extensively burnt (Allan and Southgate, 2002).

Conservation or national parks constitute about 4% of the study area. Twenty years ago, over half of Australia's species of endangered mammals, more than a third of its threatened bird species and about one tenth of its threatened plant species occurred in the arid and semi-arid lands (Morton et al., 1995), and the decline is continuing (Woinarski and Fisher, 2003). The parks and reserves are refuges for animals and fire sensitive plant species, as well as being important scenic locations for tourism, and so have their own unique fire management issues.

Other land uses in the arid and semi-arid regions of Australia include tourism, mining, harvesting of wild animals and plant products, and horticulture.

All these stakeholders have different ecological, cultural and economic priorities, outlooks and management strategies about fire which can affect fire regimes in a particular area (Edwards et al., 2008). Regimes can also potentially be affected by other factors such as climate change (Allen Consulting Group, 2005; Pittock, 2003) or the spread of fire-prone weeds (Butler and Fairfax, 2003; Friedel et al., 2006; Pitt, 2004).

5.3 Methodology

Continental FAA and FHS datasets were compiled by DLI for a seven year period from 1998 to 2004. The methodology followed is explained in detail by Craig et al. (2002). For the FAA data, daytime satellite images are used to delineate the areal extent of fires on a nine day cycle. Although the nominal resolution of the AVHRR sensor is 1 km^2, the minimal area mapped as FAA is 4 km^2. Evening satellite images are used to detect active fires (FHS) on a daily basis and these are mapped at a 1 km^2 resolution. Spatial climate datasets were purchased from the Bureau of Meteorology.

All further processing of these datasets was performed with standard geographical information system (GIS), spreadsheet, and statistics software.

The FAA dataset contains the areal extent and location of each mapped burnt patch and the date when it was detected. This date can be some time after the actual fire event, due to the nine day processing cycle, and smoke or cloud cover in some satellite images. The data was summarised by year/month for this analysis.

The FHS dataset contains the location of each detected active fire, the date and time when it was detected, along with the satellite and orbit numbers. Almost half of the 873,463 hotspots mapped in the study area where tagged as “possible” fire hotspots. For the purpose of this study, these records were ignored, and only the records tagged as definite hotspots were analysed. Hotspots associated with heavy industry with either gas flares or industrial chimneys were also deleted from the dataset (Dampier and Kalgoolie in W.A., Mt. Isa in Queensland and Moomba, Roxby Downs and Whyalla in S.A.).

The remaining records were summarised for each year/month (i.e. a hotspot was detected for a given location within a given year/month or not). Similar to Gill et al. (2002b), FHS locations which were burnt in the previous month were considered re-ignitions and were also discarded, resulting in almost 400,000 monthly FHS records for analysis.

It has been estimated by DLI that there can be a mismatch between the real location of a FHS with that declared on the processed image of as much as 3 km, and often about 1 km (one pixel) (Gill et al., 2002b). As in the State of the Environment reporting (Gill et al., 2002b), any hotspots (FHS) that are associated with a burnt area (FAA) that is up to three months after the month of the hotspot record, were regarded as being a match. The distance of each hotspot from the nearest fire affected area (FAA) that fell within a three month lag period was calculated using standard GIS software.

To describe the distribution of detected fires, FAA and FHS records were analysed, both annually and in total. This was done for the entire study area, and also by individual climate zones. Area burnt and hotspot numbers were summarised within the GIS, and the results exported to a spreadsheet for further analysis and plotting.

The amount of area burnt each year was also examined in relation to the antecedent rainfall. Rainfall data for each year (1996 to 2003) was reclassified spatially into 200 mm categories in the GIS. This resulted in 56 records, as not all categories were present in every year. Each year’s rainfall category data was intersected with the FAA data from the following year. The percentage of area burnt in each category was calculated, and linear regression performed on the results.

Seasonality was examined by summarising area burnt and hotspot numbers on a month-by-month basis by climate zones, both annually and in total.

The number of years each FAA and FHS location was burned (the burn frequency) over the study period was calculated. This was done by creating a grid of 1 km2 cells for each year within the GIS, with a value of 1 for burned or 0 for unburned for each cell. By adding these grids together the number of years that each cell burned was calculated.

Combining the FAA grids produced another grid showing the particular years each cell burnt. From this the minimum return interval (the shortest time between fires), was calculated for each cell that had burnt more than once.

To analyse the size or extent of FAA records, burnt patches which had their centroids in the study area were selected. These data were then divided into five orders of magnitude for analysis, and summarised by both number and area for each climate zone. Fire hotspot records, by definition, do not have an area associated with them.

5.4 Distribution of Fire Records

Between 1998 and 2004 nearly 60% of both the FAA and FHS records for the entire country were within the arid and semi-arid lands (figure 5.2). All further statistics in this paper refer only to the FAA and FHS data within the study area. Almost 27% (over 1.5 million km2) of arid and semi-arid Australia was mapped as burnt at least once in the FAA dataset, the majority in the northwest. As some areas were burnt repeatedly, this totalled almost 2.3 million km2 of mapped burnt areas. Almost 7% of all possible locations (at a 1 km2 resolution) had an active fire (FHS) detected, and over 6% of these locations had fire hotspots recorded a number of times.

Within the study area, over 46% of the FHS fell directly within a matching FAA (i.e. mapped within 3 months of the hotspot). About 10% fell 1 km outside an FAA, and another 10% between 1 and 3 kms away. All of these were within the limits of the spatial accuracy of the FHS dataset (Gill et al., 2002b), and were quite likely to be part of the same fire that caused the FAA. The remaining third of hotspots were not associated with an FAA. Many of these were likely to be small fires (less than 4 km^2) which were not detected in the FAA mapping. Some, however, were part of larger fires which were not mapped in the FAA dataset.

Within individual climate zones (figure 5.1), the proportion of recorded fire (i.e. the percentage of the total FAA and FHS) in the two datasets was generally similar (figure 5.3). The biggest differences were in zone 13 (the north), and zone 15 (particularly in the eastern states). In the north, the proportion of FAA was substantially greater than the proportion of FHS, which may be due to greater cloud cover in the build-up to the monsoon season and/or smoke from larger fires in this region. These obscure the view of the satellites on any given day when fires are actively burning (FHS), while the burnt area (FAA) can still be detected at a later date. In zone 15, the higher

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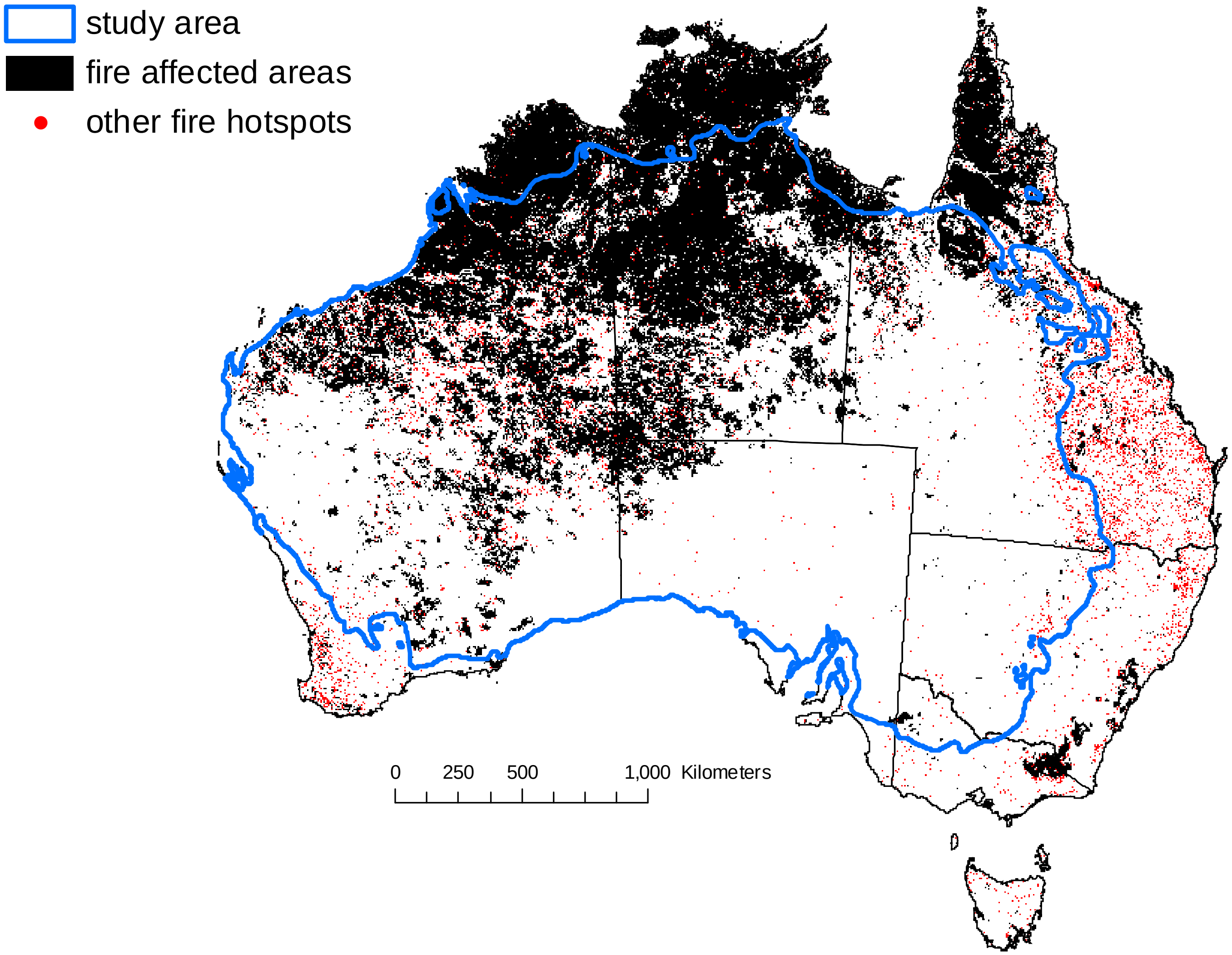

Figure 5.2 Australia-wide fire affected areas (FAA), and fire hotspots (FHS) not associated with an FAA, 1998 - 2004

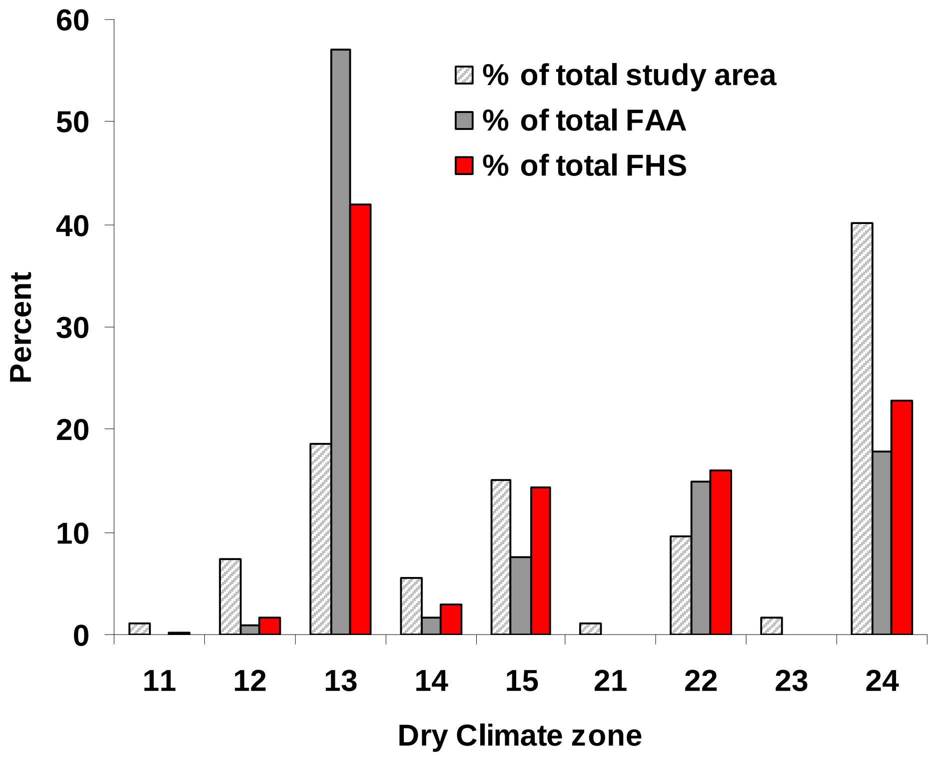

Figure 5.3 Percentage of total study area, FAA, and FHS per dry climate zone, 1998 – 2004

Climate zones based on Stern et al. (2000)

Percentage of study area = km2 of zone / km2 of total study area * 100

Percentage of total FAA = km2 of FAA in zone / km2 of total FAA * 100

Percentage of total FHS = count of FHS in zone / count of total FHS * 100

proportion of FHS reflects the greater number of small fires compared to larger ones, especially in the more intensively managed pasturelands in the eastern states.

The percentage of each zone mapped as FAA, and the density of hotspots, both followed the general decrease in annual average rainfall from north to south (table 5.1). Both the greatest area and density of fire was recorded in the north in climate zone 13. While it covers less than 19% of the study area, 57% of the total burnt area (FAA) and 42% of all hotspots occurred here (figure 5.3). The proportion of burnt area (FAA) compared to the area of the zone itself was 124%, because many locations were burnt repeatedly. In zone 22 this dropped by half to 62%. These two zones also had the highest density of hotspots - almost 16 and 12 per 10 km2 respectively (table 5.1). Moving south, the proportion of area mapped as burnt in the FAA dataset, and the density of hotspots, dropped substantially in zones 15, 24 and 14. Here almost 20%, 18% and 13% of the zones' area burnt respectively. Hotspot density was highest in zone 15, at almost 7 per 10 km2, influenced by the many small fires in the east, and was around 4 per 10 km2 in the other two zones.

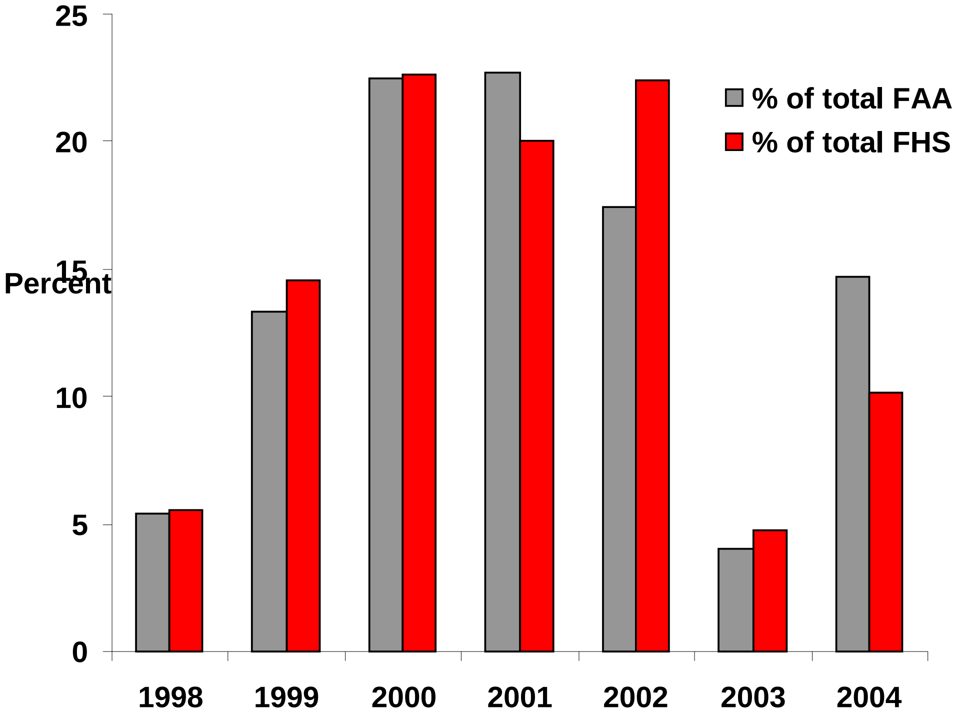

Figure 5.4 Percentage of dry climate zone FAA and FHS per annum, 1998 – 2004

Percentage of total FAA = km2 of FAA in year / km2 of total FAA * 100

Percentage of total FHS = count of FHS in year / count of total FHS * 100

There was significantly less fire in the south in climate zones 11, 12 and 21, and least in zone 23 in the west. The proportion of the area burnt ranged from less than 5% to just over 1%, while hotspot densities were between 1.5 and 0.2 per 10 km2 (table 5.1).

There was a great degree of annual variation within this relatively short time span (figures 5.4 and 5.5b). During the seven years, an average of 5.75% (328,109 km2) of the study area was mapped as FAA annually, but this varied from a low 1.6% in 2003, to over 9% in both 2000 and 2001.

Figures 5.5 and 5.6 show the relationship between the pattern of FAA in any given year, and the previous year’s rainfall totals. In 1998 fire (FAA) was concentrated in the north, while in 1999 it spread further across the northwest. Following on from above average rainfall, vast areas burnt in the western half of the study area in 2000, with as much area burnt in the desert as in the north. A similar amount of area was burnt in both 2001 and 2002, again following the pattern of above average rainfall in the previous year. In 2001 fire was more concentrated in the north again and generally further east into the Northern Territory, while in 2002 the majority of burnt area was in the Northern Territory and extending across the border into South Australia. After a very dry 2002 in general, 2003 was a low fire year throughout the study area, while fire was once again concentrated in the north in 2004.

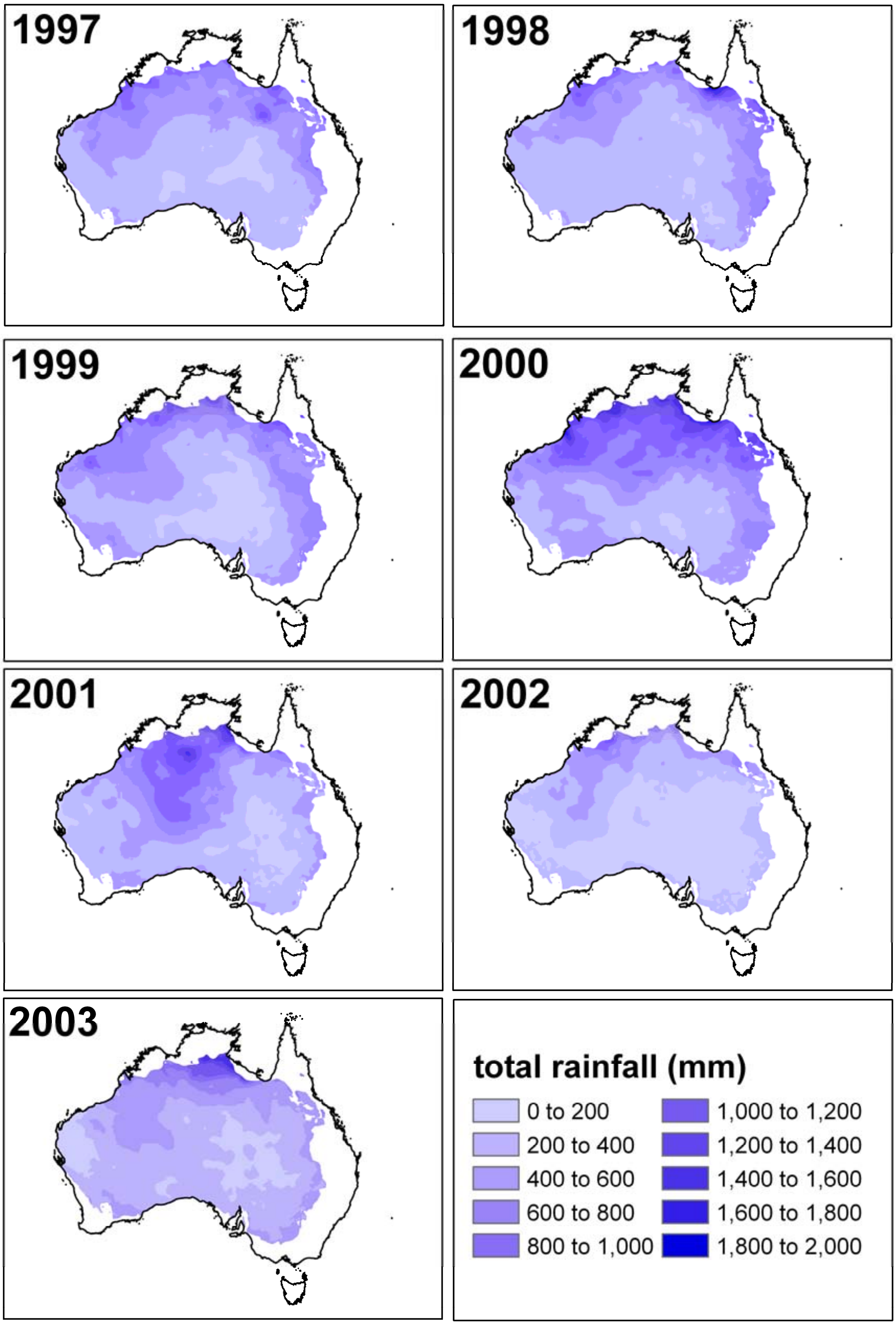

Figure 5.5 (a) Total dry climate zone rainfall per annum, in 200 mm categories, 1997 – 2003

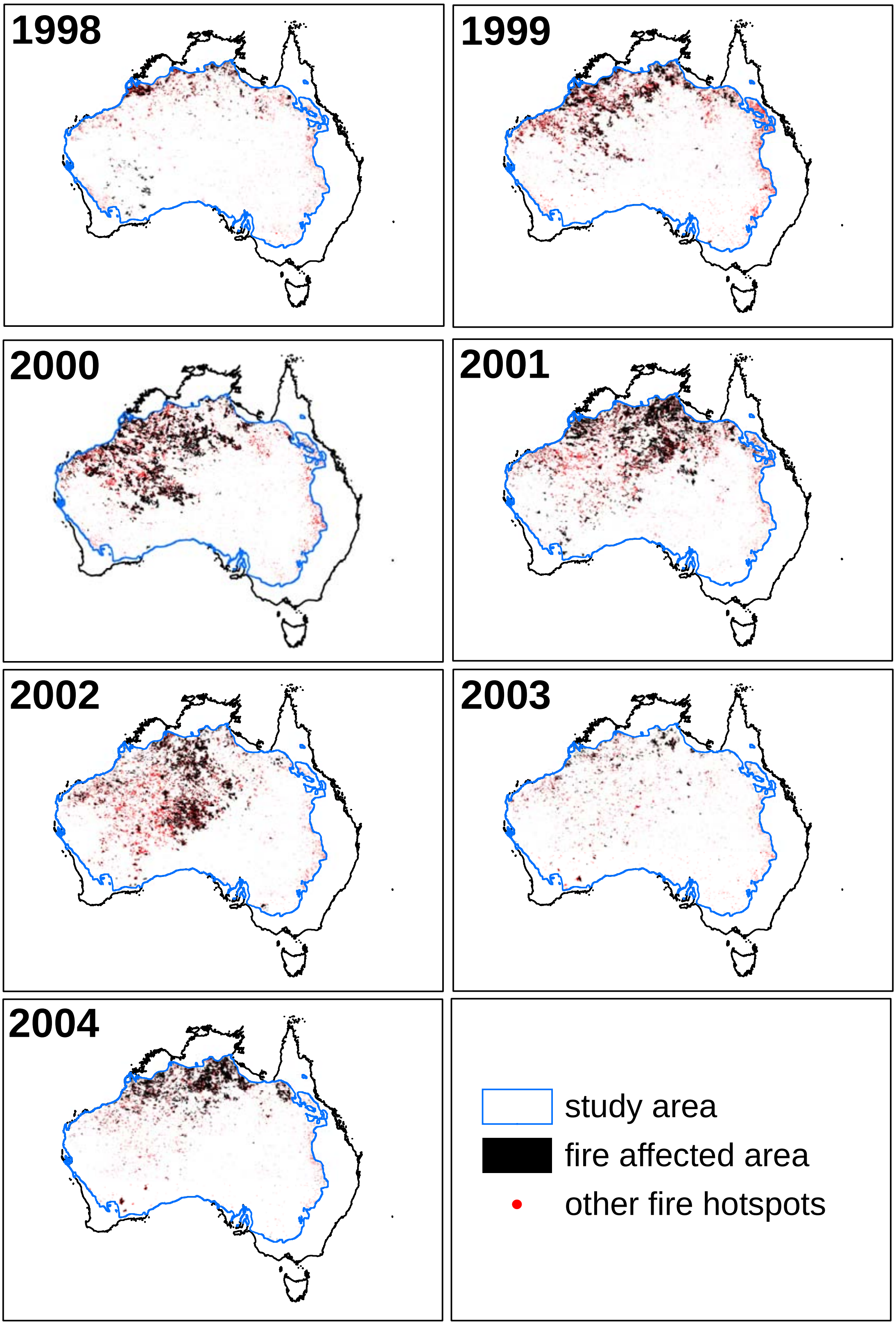

Figure 5.5 (b) Dry climate zone FAA and FHS per annum in the following years, 1998 – 2004

Comparing the categories with high total rainfall from one year, with FAA from the following year, reveals a marked similarity in pattern (e.g. 2001 rainfall and 2002 FAA).

Table 5.1 FAA and FHS per dry climate zone

Climate zone and description as defined by Stern et al. (2000)

Fire seasonality category as defined in this paper

Percentage of total study area = km2 of zone / km2 of total study area * 100

Percentage of zone burnt = km2 of FAA in zone / km2 of zone * 100

Density of FHS per 10 km2 = count of FHS in zone / km2 of zone * 100

Climate zone	Description	Fire seasonality category	% of total study area	% of zone burnt	Density of FHS per 10 km^2
		Grasslands			
11	Warm, summer drought	West	1.0	2.5	1.5
12	Warm, persistently dry	South	7.3	4.8	1.5
13	Hot, winter drought	North	18.5	124.0	15.9
14	Hot, summer drought	West	5.4	12.6	3.7
15	Hot, persistently dry	Central	15.0	20.0	6.7
		Desert			
21	Warm, persistently dry	South	1.2	3.0	0.2
22	Hot, winter drought	North	9.6	62.1	11.6
23	Hot, summer drought	West	1.7	1.4	0.3
24	Hot, persistently dry	Central	40.2	17.8	4.0

While fairly similar in overall pattern, there were some differences annually between FHS and FAA (figures 5.4 and 5.5). In the western half of the study area, 2002 was the year of maximum FHS, while FAA peaked here in 2000. Many of the 2002 fires in the west would appear to have been smaller than those in 2000, as they had no associated FAA record. Approximately 10% of all FHS were in the southeast half of the study area, but most of these were not associated with corresponding FAA. Here, 1999 was the most significant FHS year, followed by 2000 and 2001. These were the years preceded by the highest rainfall in the east. There was less activity in other years, associated with times of below-average rainfall.

The relationship between FAA and antecedent rainfall was measured using a simple linear regression on what proportion of each rainfall category was burnt the following year (e.g. how much of the area with rainfall between 200 mm and 400 mm in 1997, was burnt in 1998 etc.). Initial results showed a positive relationship, with an r2 of 0.28, explaining less than 30% of the variation in the data. Further examination of the data highlighted that rainfall categories with small areas were influencing the trend greatly. When categories with an area less than 0.5% of the total study area were treated as outliers and removed, the r2 rose to 0.74 (figure 5.6), with a p-value < 0.0001. The five outliers still remaining, which form an arc at the top of figure 5.6, are all values relating rain in 2003 with FAA in 2004. Because 2003 was such a dry year in general, these higher rainfall categories had very small areas (four of them around 1% of the study area), and were confined to the very north of the study area which burns regularly. If these are removed the r2 increases to 0.86.

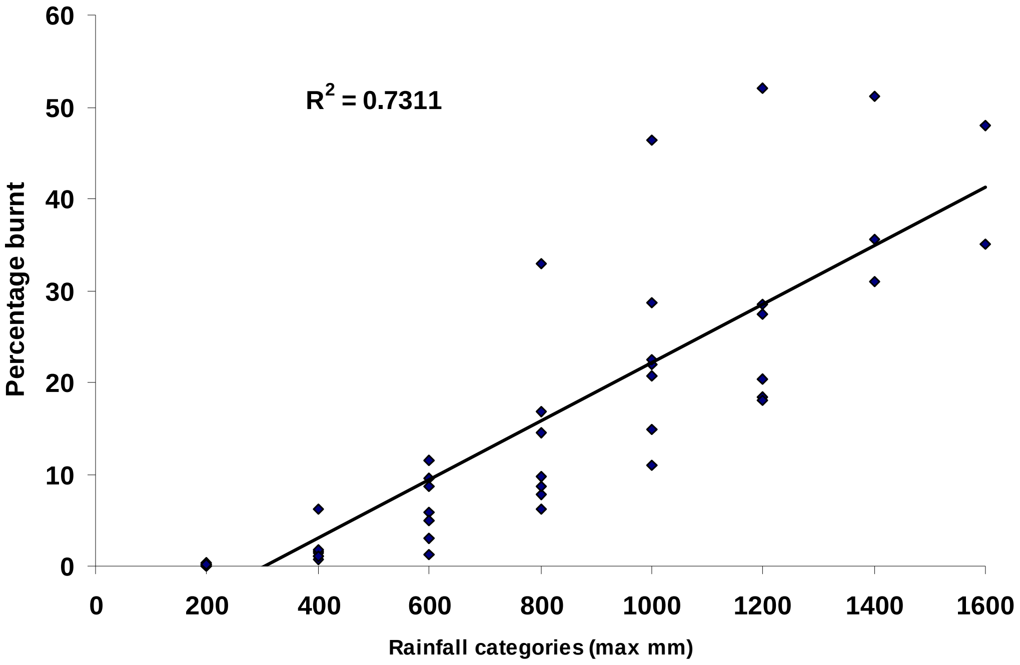

Figure 5.6 Linear regression analysis of the effect antecedent rainfall has on the percentage of area burnt (FAA) the following year, in the dry climate zones

Comparing rainfall categories from 1997 – 2003, with FAA from 1998 – 2004. Each point represents how much of a particular rainfall category for a particular year, was burnt the following year.

If the 5 outliers forming an arc, (which are all rainfall categories from 2003 with small areas), are removed, the r2 increases to 0.8608.

5.5 Seasonality

Fuel accumulation and curing follow differences in the seasonal distribution of precipitation and temperature. In these dry climates the fuels cure every year. In the wetter northern areas, there is an accumulation of fuels (mainly grasses and herbs) across the landscape every year. While further south, extensive fires occur when continuity of fuel is increased by the growth of annuals between spinifex hummocks, as a consequence of episodic years of above-average rainfall (Myers et al., 2004).

The seasonality of fire events, as well as the quantity, varied considerably across the study area (figures 5.7 and 5.8). After examination by individual climate zones (figure 5.1), the fire data were grouped into four categories - north, west, central and south – for zones showing similar patterns (table 5.1). These are characterised by whether they have a winter drought, a summer drought, or warm or hot persistently dry conditions. The overall pattern of seasonality of the FAA and FHS data within each category was almost identical (figure 5.8), with some variation from the general trends over individual years.

The northern category (climate zones 13 and 22), is defined as being hot with a winter drought. This category had the greatest proportion of fire, with the majority in zone 13 (figure 5.3). It covers almost 30% of the study area, with over 70% of the total FAA and almost 60% of the FHS. A distinct bimodal distribution was evident here (figure 5.8). The smaller peak can be seen in both the FAA and FHS data at the start of the dry season around May, particularly in zone 13. The main peak in fire activity for FAA was at the end of the dry season, from September to November, with a significant increase in area burnt from previous months. Fire hotspots peaked in September/October, but dropped off more than FAA in November. As discussed in the previous section, this difference between FAA and FHS may be caused by thick cloud during the build-up to the wet season in the tropics and/or smoke obscuring active fires. The least amount of fire was during the wet season between January and March, although some fires occurred even then.

Climate zones 15 and 24 are classified as hot and persistently dry, but during the timeframe of this study there were a number of years of above average rainfall in these zones. This resulted in this central category having a large proportion of the fire. It covers over 55% of the study area, and had over 25% of the total FAA and 37% of FHS (figure 5.3). There is more annual variation here than in the north, with a large difference in the percentage of area burnt from year to year. Overall the season peaked in September/October, with FHS remaining at its peak in November, and both FAA and FHS tapering off in February (figure 5.8). However, in low fire years, fire tended to peak later, between November and February for FAA and November to January for FHS.

The western category (which also has a small area of zone 11 in South Australia), is characterised by summer droughts, with climate zones 14 and 23 being hot, and zone 11 warm. It occupies 8% of the study area and had less than 2% of the total FAA and 3% of FHS, the vast majority in zone 14 (figure 5.3). The fire season here peaked in December to February for FAA and November to January for FHS, with a slight secondary peak around April in FHS (figure 5.8).

Warm persistently dry conditions define the southern category (zones 12 and 21). It is slightly larger than the western category, but had less fire (1% of the total FAA and 1.6% of the FHS), with practically none in zone 21 (figure 5.3). The seasonality of fire is quite similar to the western category, with FAA peaking between December and February, and FHS continuing on into April (figure 5.8). In these low fire areas, just one fire has the potential to change the statistics dramatically, depending on its size.

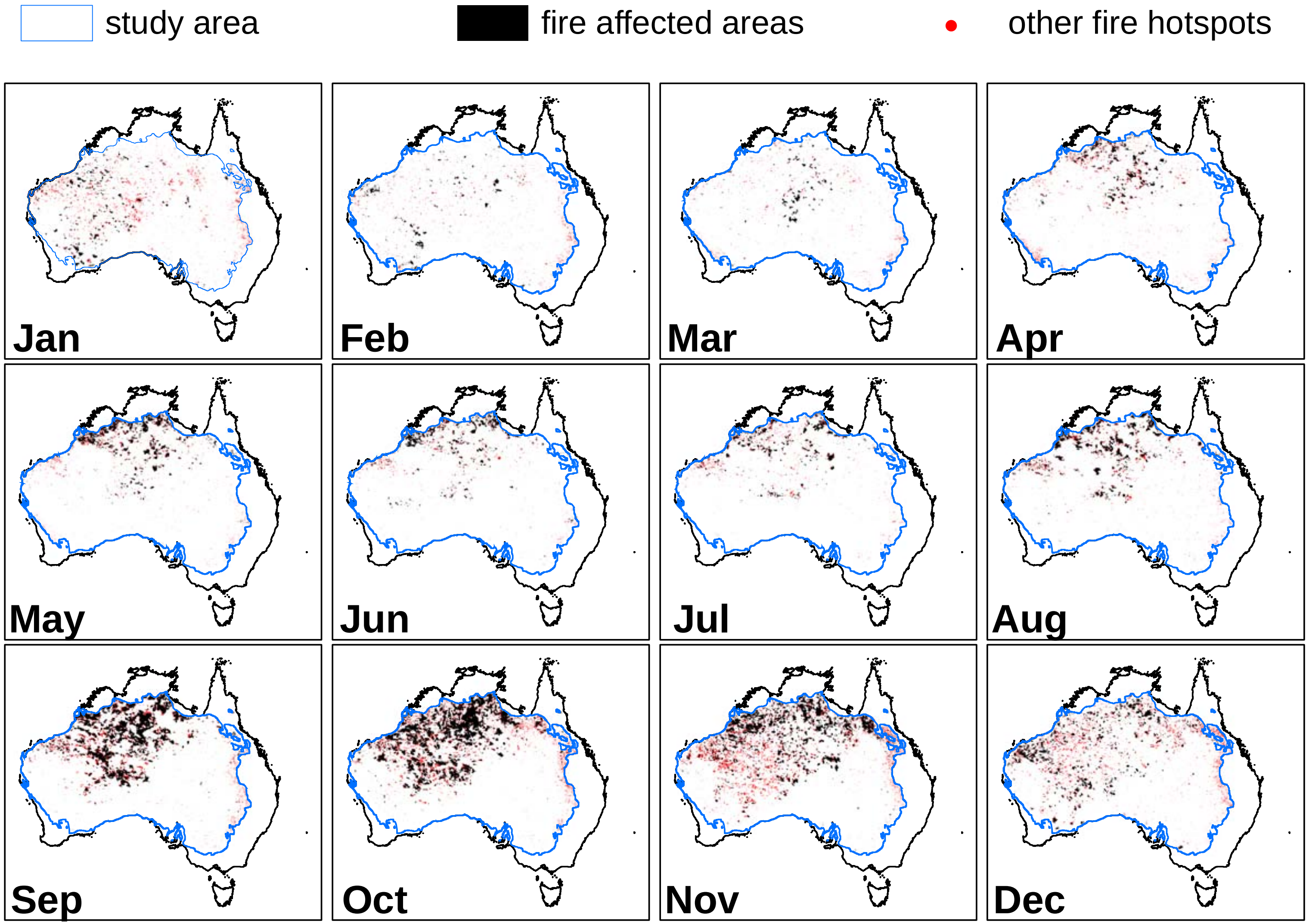

Figure 5.7 Dry climate zone FAA and FHS per month, 1998 – 2004

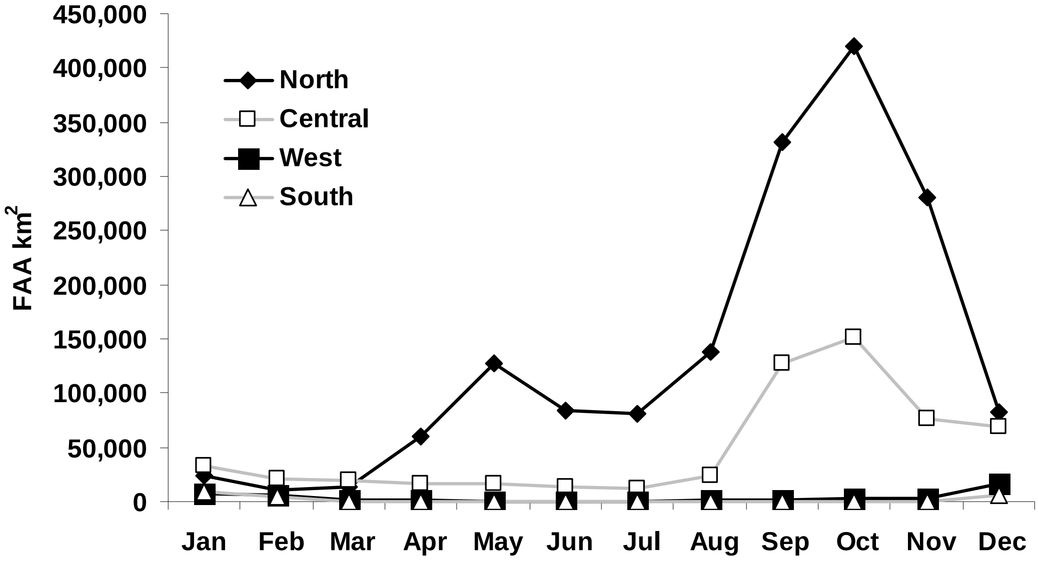

Figure 5.8 (a) Area of FAA per month by dry climate category, 1998 – 2004

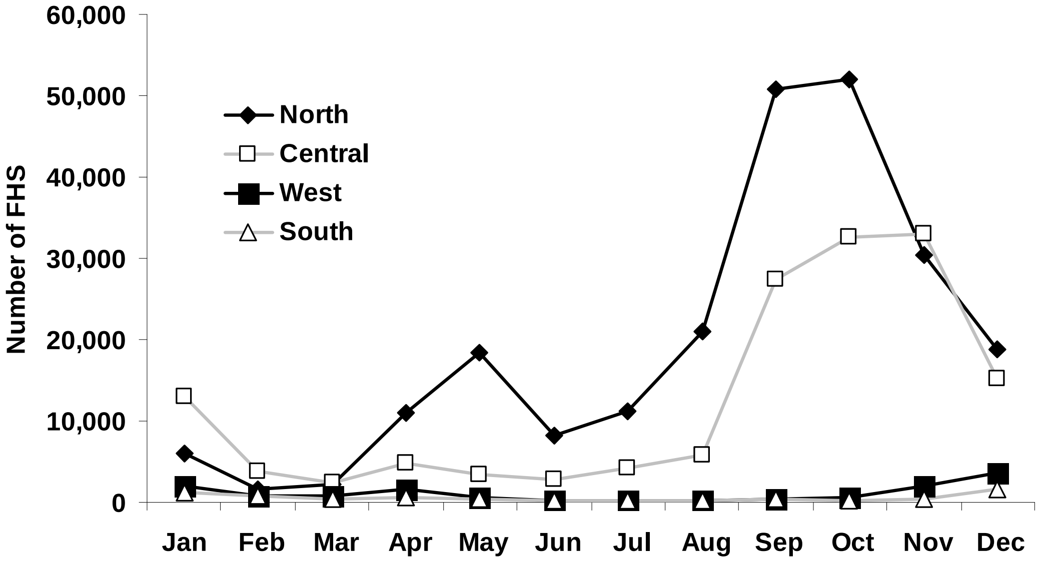

Figure 5.8 (b) Number of FHS per month by dry climate category, 1998 – 2004

Dry climate categories: north – winter drought; central - hot, persistently dry; west – summer drought; south – warm, persistently dry. Based on Stern et al. (2000).

5.6 Frequency and Minimum Return Interval

Within any given year, in essence, areas were not burnt more than once. Only 170 km2 were mapped in the original FAA dataset as being burned twice in the same calendar year for the entire period. Manual examination of these areas showed them all to be the adjoining edges of a number of burnt patches. They were subsequently assigned the month in which they were first mapped.

Figure 5.9 shows the number of times any given area was burnt (FAA) between 1998 and 2004. About three quarters of the study area had no recorded FAA at all, predominantly the southeast half and another area in the southwest of WA. Of the remainder, over 17% of the study area had FAA which was burnt only once, almost 6% was burnt twice and about 2% three times. Less than 1% of the FAA was mapped as being burnt four times or more (i.e. over 66% of all FAA burnt once, about 22% twice, 8% three times and 3% four or more times). The areas that burnt more than once were predominantly in the wetter northern regions. There was also an area in the Central Ranges, around the NT, WA, SA border that was burnt two or more times. The few areas that burnt four or more times were in the far north.

By comparison, there were almost 375,000 locations (7% of all possible locations at a 1 km2 resolution) where hotspots (FHS) were mapped at least once. The vast majority (over 93%) of these only had one period in which they were recorded. A significant number (almost 6%) were also mapped in two different fire months. These were scattered throughout the areas of greatest hotspot activity in the northwest half of the study area, the southwest corner, and along the eastern edge. Like the FAA, the locations that burnt more than twice were predominantly in the north and a small area around the Central Ranges, as well as some additional areas in the eastern strip of fairly dense FHS. Only 1,313 hotspot locations were mapped as burning three times, and less than 100 four or more times.

Some areas within the study site are known to have fire return intervals (the average time between fires) of 20 to 50 years (Allan and Southgate, 2002). Because of the relatively short time period that this data covers, it was not possible to estimate meaningful fire return intervals. However, from the data available, a minimum return interval (the shortest time between fires) for this period could be calculated for those areas which burnt twice or more. Only the FAA dataset was used in this analysis. We could calculate a minimum return interval for one third of the area that was burnt (9% of the total study area) from 1998 to 2004. Of this, the most common minimum return interval was two years (36%), with one and three years accounting for around 27% and 21% respectively. These areas were mostly in the northern sector, and the area of repeated burns in the Central Ranges.

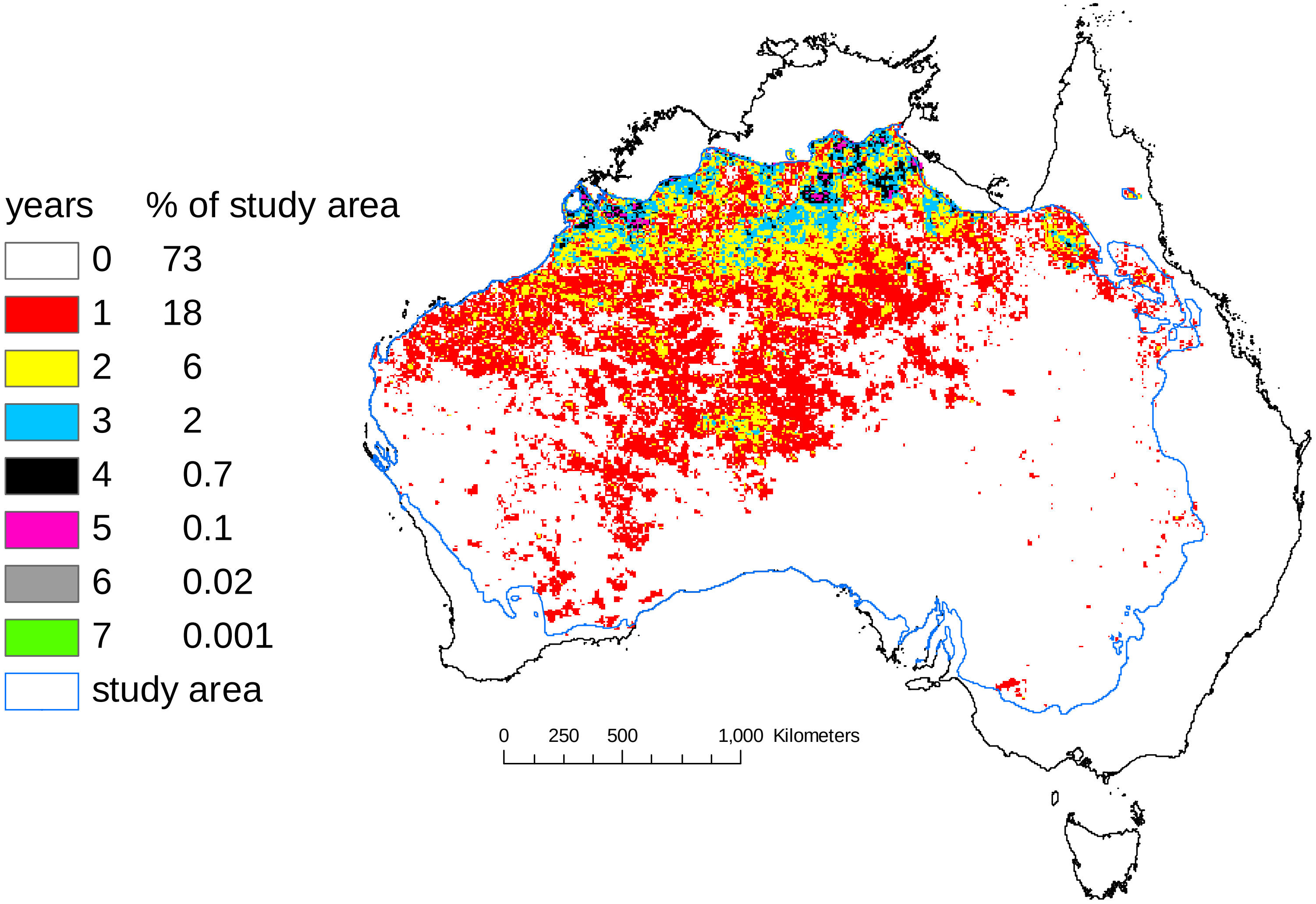

Figure 5.9 Number of times dry climate areas burnt (FAA) between 1998 and 2004

5.7 Number and Extent

Care should be taken when interpreting the data in this section. Although it refers to the ‘number’ and ‘extent’ of FAA, this does not translate directly into the number and extent of actual fires. There is no attempt to identify individual fires in this dataset. A mapped ‘patch’ (individual Fire Affected Area record) may in fact be the sum of a number of fires with a common boundary. On other occasions, an individual fire may be mapped as several individual patches, particularly as it spreads over time.

A total of 24,634 FAA patches with their centroid in the study area had been mapped, totalling 2,299,410 km2 (with about one third of the areas being burnt more than once). These were analysed by five orders of magnitude per climate zone (table 5.2).

Overall, there was a good representation of FAA in the first three size categories (less than 10 km2, 10 to 100 km2, and 100 to 1,000 km2) in all climate zones except zone 21. However, FAA between 100 and 1,000 km2 are less well represented in the southeast half of the study area. While FAA greater than 1,000 km2 were not so numerous, they were not uncommon, with over 300 patches recorded, even occasionally in the low fire activity areas. Only two patches over 10,000 km2 were mapped in the entire study area in this timeframe (almost 10,500 and 23,500 km2), both in the north in climate zone 13.

A little over 56% of mapped patches were between 10 and 100 km2, but accounted for only just over 20% of the total burned area. It was the most common category by number in all climate zones. By contrast, 17% of patches are responsible for almost 52% of the burned area. These were the FAA between 100 and 1,000 km2.

A similar reversal can be seen in the category less than 10 km2, where 25% of patches accounted for 1.5 % of the total burned area, and the category between 1,000 and 10,000 km2, where 1.3% of FAA records accounted for 24% of the burned area.

Between 50% and 60% of patches were between 10 and 100 km2 in all years apart from 1998, when 50% of patches were less than 10 km2. There was a general tendency for low fire years to have a greater proportion of the patches under 10 km2, and for more patches between 100 and 10,000 km2 in high fire years.

The majority of patches under 10 km2 occurred in the winter in the north (climate zones 13 and 22), in winter/spring in the central zones (15 and 24), and in summer/autumn in the west and south. In all other size categories, the greatest number of patches was generally in spring in the north and central zones, and in summer in the west and south.

Table 5.2 The number and area of FAA patches (which are not necessarily individual fires) categorised in five orders of magnitude by dry climate zone

For example, there were 9 FAA records, each with an area between 10 and 100 km2, with their centroid in zone 11. The combined area of these 9 records was 148 km2. The total number of records, and their combined area, are calculated for each category, as well as their percentage of the grand totals.

Climate Zone	Patches 0 - 10 km^2		10 - 100 km^2		100 - 1,000 km^2		1,000 - 10,000 km^2		< 25,000 km^2	
	#	Tot km^2	#	Tot km^2	#	Tot. km^2	#	Tot. km^2	#	Tot km^2
					Grasslands					
11	8	43	9	148	5	1,422	0	0	0	0
12	42	216	106	4,318	35	9,603	3	5,062	0	0
13	3934	21,613	7655	262,899	2313	648,702	187	341,781	2	33,894
14	194	1,225	427	14,681	86	20,911	2	2,141	0	0
15	578	3,546	1571	51,353	380	94,718	14	24,828	0	0
					Desert					
21	0	0	4	145	0	0	2	2,376	0	0
22	613	3,728	1767	64,043	642	183,878	57	90,949	0	0
23	7	46	21	542	3	717	0	0	0	0
24	827	4,825	2262	79,324	820	230,254	58	95,478	0	0
Total	6,203	35,242	13,822	477,454	4,284	1,190,205	323	562,615	2	33,894
% of Grand Total	25.18	1.53	56.10	20.76	17.39	51.76	1.31	24.47	0.01	1.47

5.8 Discussion

The arid and semi-arid rangelands have a high biodiversity value and are relatively undisturbed, but there is evidence that inappropriate fire regimes are affecting the abundance and richness of biodiversity (Benson, 2001; Letnic and Dickman, 2006; Myers et al., 2004; Woinarski and Fisher, 2003). When formulating management plans, it is important to know what fire regimes are currently operating in particular areas, and to use this information as a benchmark against which to measure the effectiveness of management strategies.

Limited reliable quantitative information has made it difficult to calculate or describe current fire regimes, and impossible to determine change from past regimes, throughout most of the arid and semi-arid rangelands (Allan, 2003; Burrows et al., 2006a). Little is known about pre-European fire regimes in these dry landscapes (Bowman, 1998; Fensham, 1997; Gill, 2000; Kimber, 1983). Until recently, the majority of the rangelands have had no mapped fire history, and analysis has been limited in either spatial or temporal extent.

Evidence from the limited research does suggest that fire regimes have changed since European settlement. In appears that, in some areas at least, the traditional Aboriginal regime which created a fine-grained mosaic of vegetation at different stages of post-fire succession (Latz and Griffin, 1978), has been replaced with a simpler mosaic consisting of either vast tracts of long un-burnt vegetation, or vast tracts of vegetation burnt by large and intense lightning-caused wildfires (Allan and Southgate, 2002; Bradstock and Cohn, 2002; Burrows et al., 2006a; Craig, 1999).

Fortuitously, our study enabled us to analyse mapped fire events for the whole of arid and semi-arid Australia during a period of widespread fire for the first time, within the relatively short timeframe (1998 to 2004). This information will help inform policy makers of the potential extent and significance of fire in certain regions, albeit low in frequency. We now have a snapshot of fire patterns in both high and low fire years on which to base current management decisions. While we do not have reliable reports of past widespread fire events for many parts of the study area to compare with the new FAA and FHS data, our data should be useful for future comparisons. Our analysis shows that there are a range of fire regimes currently operating throughout the area, exhibiting complex spatio-temporal patterns. It highlights the differences across rainfall gradients, between high and low rainfall periods, and between and within climate zones. The study has also highlighted areas which may require more intensive investigation, such as the areas in the Central Ranges which stand out as being burnt more frequently than surrounding regions.

Between 1998 and 2004 almost 27% of arid and semi-arid Australia burnt at least once. The main trends in fire distribution follow latitudinal rainfall gradients, dropping dramatically towards the south. While there was generally less large scale fire in the east, there was a concentration of smaller fires along the eastern edge, captured by the hotspot detection. Within these trends, regression analysis also shows a strong relationship with the pattern of antecedent rainfall. The seasonality of fire events varies between climate zones in accordance with the varying distribution of precipitation and temperature, which influence fuel accumulation and curing. Areas that burnt more than once were predominantly in the wetter northern regions. The majority of mapped burnt patches were between 10 and 100 km2, but with a tendency for a greater number of large patches following above-average rainfall.

The study has shown the importance of using the FHS dataset in conjunction with FAA, especially in areas of low fire activity, in order to build a more complete perspective of fire. The FHS and FAA datasets are at a relative coarse scale and are both known to be an underestimation of the amount of fire in the landscape (Gill et al., 2002b; Yates and Russell-Smith, 2002). A combination of the two techniques overcomes some of the deficiencies. Whereas the FAA data gives the area of the fire, some fires are too small, or the burn results in little change of reflectance pattern, and they remain undetected. These fires may still be detected as hotspots but without a size estimate. The size of fires has important implications for humans living in the affected areas. Large wildfires pose a direct risk to life and property, and even deliberate landscape burning can be a health hazard due to smoke exposure (Johnston et al., 2006).

Regression analysis has shown that rain is a major driving force behind the fire regimes in arid and semi-arid Australia. The fire patterns are further influenced by other factors such as soil and vegetation type, land use and tenure, management strategies, population density and demographics, road and track networks, lightning, topography, and local weather conditions (Allan and Southgate, 2002; Bowman, 1998; Edwards et al., 2008; Hodgkinson, 2002). While this paper has been largely descriptive, further in-depth statistical analysis is necessary in order to determine what spatial and temporal relationships currently exist between these climatic, edaphic and anthropogenic factors.

Changes in any of these factors have the potential to alter fire regimes. Over the last 50 years Australia has experienced increases in rainfall across the northwest, and decreases over much of the southeast, while average temperatures have risen by 0.7 ºC over the last century (Pittock, 2003). Australia will face some further degree of climate change over the next 30 to 50 years irrespective of global or local efforts to reduce greenhouse emissions (Allen Consulting Group, 2005). The invasion of buffel grass (Cenchrus ciliaris), a perennial grass introduced to central Australia for pasture and landscape rehabilitation, has the potential to change fire regimes in many areas (Butler and Fairfax, 2003; Friedel et al., 2006; Pitt, 2004). It responds rapidly to relatively low amounts of rainfall, with the high rate of biomass accumulation increasing the potential for more frequent and higher intensity fires, creating a positive feedback loop. The patterns of fire between the two most recent periods of widespread fires (1974-77 and 2000-02) throughout the southern portion of the NT were very different (Edwards et al., 2008). There was higher fire activity in the cooler months of March to August during 2000-02, purportedly started by human-ignition, often from roadsides. It is suggested that changes in population demographics, an increase in accessibility to remote areas, and changes in land tenure due to Aboriginal land claims, all contributed to this change.

It is important to maintain continental databases such as the FAA and FHS, and supplement them with higher resolution mapping in areas requiring particular attention. Other databases of the factors which affect fire regimes must also be updated regularly, if they are to be of any real benefit to this type of analysis, as they are in a constant state of flux. Maintaining these databases, and undergoing this type of analysis at regular intervals, will help increase our understanding of the fire regimes in arid and semi-arid Australia from this initial overview, and highlight when, where and why changes are occurring.

A better awareness of the regional patterns of fire will hopefully encourage a more collaborative, cooperative and coordinated approach to fire management between political jurisdictions, landowners and managers, cultures and individuals (Edwards et al., 2008). By using fire in an appropriate manner, not only can stakeholders protect their livelihood and reduce the cost and impact of wildfires (Craig, 1999; Uluru-Kata Tjuta Board of Management and Parks Australia, 2000), they can use appropriate fire management practices to assist with and enhance productivity of existing and potential industries e.g. pastoralism and bush tucker (Craig, 1999; Letnic, 2004; Myers et al., 2004; Vitelli and Pitt, 2006). Improved fire management has long-term benefits to biodiversity (Gill et al., 2002a; Gunawardene and Majer, 2005; Keith et al., 2002), and direct benefits to associated ecotourism dependent endeavours.