# From Ashes to dust: The role of land use in determining fire frequency and erosion risk in rural NSW

**By**

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# Candidate's Declaration

Honours in the Fenner School of Environment and Society comprises two distinct courses - ENVS4001 (Honours Research Skills) and ENVS4000 (Honours Thesis). Draft versions of the content of Chapter 2 of this thesis were originally submitted for assessment during the Honours midcourse review, which is part of ENVS4001. These chapters have since been modified extensively and are submitted in final form in this thesis for assessment as part of ENVS4000.

To the best of the author's knowledge, this thesis contains no material previously published or written by another person, except where due reference is made in the text.

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## List of abbreviations

| | |
|---|---|
| DJF | Summer months, December, January, February |
| ENSO | El Nino Southern Oscillation |
| FFDI | McArthur Forest Fire Index |
| FIRMS | Fire Information Research Management System |
| GIS | Geographical Information System |
| IOD | Indian Ocean Dipole |
| IPO | Interdecadal Pacific Oscillation |
| JJA | Winter months, June, July August |
| LGA | Local Government Area |
| LLS | Local Land Services |
| MAM | Autumn months, March, April, May |
| MODIS | Moderate Resolution Imaging Spectrometer |
| LLS | Natural Resource Management |
| SAM | Southern Annular Mode |
| SOI | Southern Oscillation Index |
| SON | Spring months, September, October, November |
| SST | Sea surface temperature |
| VIIRS | Visible Infrared Imaging Radiometer Suite |

# Abstract


The Australian landscape is known to burn. Fire in NSW is commonly associated with instances of catastrophic forest wildfire that periodically burn vast quantities of land within the near coastal regions. However, various practices of managed burning are recognised to occur throughout the state.

The frequency of fire is linked to various forms of land degradation. The risks of accelerated soil erosion increase when groundcover is removed from burning, therefore it is essential for the management of erosion to identify conditions of frequent burning. Fire management practices, linked to land uses, are likely to affect fire frequencies, however, the association between land use and fire frequency has remained unmeasured, until now.

This thesis provides insight into the extent of fire frequency within rural NSW by use of a GIS driven comparison of associated fire densities across a 15-year sampling period. It argues land use to predetermine fire frequency in NSW, presenting evidence of distinct influences to the distribution, magnitude and seasonality of fire activity within the state.

Analysis was conducted on a range of spatial scales, over a series of chapters, from state-level to local areas within the Riverina region. The Riverina was determined to be a considerable influence on total fire detections within the state, as well as the producer of the highest fire frequencies within NSW, due to the composition of land uses within.

This research challenges common perceptions relating to the frequency of fire within select land uses. The knowledge provided may also prove beneficial to both local land management entities and community groups to identify erosion risks in areas that require intervention at a regional level.

# Contents

# Chapter 1: Introduction

The presence of fire in the Australian landscape has many impacts, extending beyond the immediate threats to human property, safety and welfare. The frequency and intensity of fire exert local influences to biotic diversity (Bird et al., 2008, Kelly et al., 2012, Mutch, 1970, Tuft et al., 2012), soil condition (Chan and Heenan, 2005, Knicker, 2007) and vegetation distribution (Edwards et al., 2008, Mutch, 1970) as well as wider ranging effects to water and air quality (Mariani et al., 2016, Pellegrini et al., 2018). Repeated occurrence of fire reduces ecosystem function and services (McKenzie NJ et al., 2017, Pellegrini et al., 2018)

Recurrent fire activity has been observed to reduce the organic carbon and nutrient content of soils (Guinto et al., 1999, Knicker, 2007), reduce soil biota (Knicker, 2007, McKenzie NJ et al., 2017), and affect the pH, structure and hydrology of soils (Chan and Heenan, 2005). Loss of vegetation is critical as it exposes soils to water and wind erosion (Knicker, 2007, McKenzie NJ et al., 2017). The displacement, transportation and deposition of sediments, nutrient imbalances, both onsite and offsite cause consequential deleterious effects on land productivity (McKenzie NJ et al., 2017).

Groundcover is critical for erosion management (Leys et al., 2017) and the removal of vegetative cover by burning has been identified as an important driver (McKenzie NJ et al., 2017). However, the association between land use and fire frequency has remained unmeasured at multiple scales (Leys, 2019).

Management induced burning is actively conducted across many land uses. It is used in agriculture to promote pasture growth and reduce nitrogen tie-up on grazing land (Tasker and Bradstock, 2006, Vermeire et al., 2005), as well as for clearing and the removal of waste residues in cropping and horticulture (Scott et al., 2010, Smith et al., 2007). Weed suppression (Walsh and Newman, 2007), pest and disease control in cropping systems (Alahmad et al., 2018, Lanoiselet et al., 2005), frost protection (Smith et al., 2007), hazard reduction (Price et al., 2015) are frequent management uses of fire.

Despite the widespread use of fire as a management tool, there is a literature bias towards the study of the intermittent, often catastrophic, episodes of unmanaged fire (Russell-Smith et al., 2007). In this study, I will explore the spatial and temporal patterns of fire occurring in managed lands. While we cannot definitively conclude land management practice associated with the fires, the known land use, season and common practices help identify the agricultural practices that produce fire throughout the Australian landscape.

## 1.1 Research approach and Aims

This research will provide insight into the extent of fire frequency within rural NSW land uses by providing a GIS driven comparison of associated fire densities across a 15-year sampling period.

Spatial analysis was conducted at multiple resolutions (State, LLS, LGA) to distinguish drivers acting at various scales and identify risk areas relating to erosion and smoke hazard. Temporal analysis (2003 – 2017) has used the MODIS fire detection product for the entire analysis.

**The aims of the study are to:**

1. Measure the distribution and frequency of Australian fire to assess the contribution of NSW to continental scale burning.
2. Investigate patterns of fire distribution and frequency within NSW, to assess erosion risks within NSW LLS regions.
3. Establish the relative fire frequencies of NSW land uses and relate to observed regional fire activity.

## 1.2 Thesis Overview

This thesis argues that land use predetermines fire frequency in NSW. While the effects of climate have been shown to drive much of Australia's fire activity on a continental scale, it has been observed that a significant proportion of fire ignitions originate from human activities and much of that is associated with cropping land uses.

In Chapter 2, there is a review of published research investigating drivers of fire activity in Australia. Chapter 3 outlines the design and methodologies of the research undertaken. Chapter 4 explores the extent of fire frequency and fire seasonality on a national scale to establish the importance of fire in NSW and identify broad-scale climate influences and trends. Chapter 5 investigates the seasonality and distribution of fire frequencies between NSW LLS regions in relation to erosion risk and the influence of ENSO. Chapter 6 measures the fire frequencies of NSW land uses, identifying fire dominant land uses and their associated seasonality as well as establishing land use change within the study period. Finally, Chapter 7 explores the relationships between fire frequency and land use between LGAs within the most fire dense LLS region of NSW.

The current study is intended to provide knowledge to aid collaboration between government and community groups in order to identify the scale of local offsite impacts of fire such as dust or smoke emissions. Valuable knowledge produced through this research could be used by local land management entities to identify high-risk areas that require intervention at a regional level.

# Chapter 2: Literature Review

Fire is viewed by many Australians to be a natural and pervasive feature of the landscape. Sharples et al, (2016) observed fire to be the most frequently experienced natural hazard within Australia. The presence, as well as the potential threat of fire exerts influence on human activities, primarily through avoidance and hazard management. Each year, an estimated area between 300,000 $km^2$ and 700,000 $km^2$ is affected by fire (Bradstock et al., 2012). Ashe et al (2009) estimated the annual cost of fire in Australia, including industrial applications, to be equivalent to 1.3% of the national GDP. The majority portion of this figure was found to be spent on preventative management.

Episodes of uncontrolled and often catastrophic fire, or ‘bushfires’, common to the temperate forest biomes of southeast Australia, have had substantial adverse outcomes to human life, health, property and environmental values (Sharples et al., 2016) As a result, the destructive capacity of bushfires have captured both media and public attention. Much of Australia’s national policy on fire use and fire prevention has subsequently been shaped by these occurrences, despite accounting for only a small portion of annual fire activity (Russell-Smith et al., 2007).

Bradstock et al (2012) remarked that greater public awareness of fire has increased the complexity of fire management, as expectations and demands from different sectors of society have needed to be accounted for. Recent concerns have extended to the properties and impacts of fire emissions, often having effects beyond the vicinity of burnt areas (Johnston et al., 2011).

## 2.1 Australia as a fire continent

Studies of contemporary fire regimes have revealed Australia to be one of the Earth's most fire active continents (Russell-Smith et al., 2003, Russell-Smith et al., 2007, Whitehead et al., 2008, Williamson et al., 2016, Yates et al., 2003). However, it has also been observed that much of this activity is highly variable, both spatially and temporally (Williamson et al., 2016). Paleo-environmental studies have revealed such variability to be apparent across multiple timescales, ranging from annual to multi-millennial (Bradstock et al., 2012).

The processes that drive the changing landscape of fire prove to be complex and varied. Fundamentally however, the distribution and occurrence of natural fire is dependent on the linked attributes of vegetation structure and seasonal variations of rainfall (Russell-Smith et al., 2007). Both factors are heavily influenced by prevailing climate conditions as well as drivers of climate variability. Yet evidence suggests that human activities have modified both the nature of Australian vegetation as well as the incidence of fire (Bradstock et al., 2012). This has transpired through activities such as the clearing and fragmentation of native vegetation (Bradstock et al., 2012), the introduction of exotic plant life (Russell-Smith et al., 2007), fire use (Smith et al., 2007) and the direct suppression of existing fire regimes (Edwards et al., 2008).

To further compound this issue, the influence of anthropogenic climate change, to which the release of carbon from human driven biomass burning is likely to contribute, is linked to increases in fire-weather and ignitions (Bradstock et al., 2014). This inter-relationship between fire, vegetation and human activities is further convoluted by the likelihood that climate change is expected to affect vegetation characteristics through increased temperatures, carbon fertilisation, rainfall variability and increased severity of fire weather (Bradstock et al., 2014), as well as influence human behaviour.

The developments of satellite remote sensing of global fire activity over recent decades have provided valuable information relating to the timing and distribution of numerous and diverse fire regimes (e.g. Bradstock, 2010; Korontzi et al., 2005, Williamson et al, 2016,), contributing to our understanding of the spatial and temporal dynamics of both natural and managed fire.  Recent national studies have not only revealed land use to play an important role in annual fire activity, but aspects of land management were found to drive the distribution and seasonality of fire activity in select regions (Korontzi et al., 2008, Smith et al., 2007) This is particularly evident in the southeast and southwest of Australia, in regions associated with cropping (Bradstock et al., 2012, Korontzi et al., 2006, Smith et al., 2007, Williamson et al., 2016).

The southeast Australian Wheat-Sheep Belt spans throughout regions within SA, VIC, NSW and QLD and has been shown to display high rates of seasonal fire hotspot density, particularly within southern NSW (Smith et al, 2007).  Covering roughly 32% of the state of NSW (OEH, 2018), activities within this active agricultural zone are likely to have substantial impacts on the total annual fire frequency of the state. However, the level of contribution from this region to overall NSW fire activity is currently unquantified.

The following review is intended to briefly explore a range of published research relating to known contributing factors to the variability of both natural and imposed fire regimes within rural NSW and Australia as a whole. The relationship between fire, vegetation, climate and human activities will be explored at various spatial and temporal resolutions to identify the changes of influence that operate in differing scales.  This distinction at scale is intended to help disentangle the conflated influences of climate and human activities in order to identify the primary driver of fire activity within rural NSW. A particular focus is given to the use of fire as a tool in agricultural management in light of the findings of Smith et al (2007) as well as the application of contemporary and accessible remote sensory products used for the detection of active fire.

## 2.2 Influences of vegetation

Fire is a key earth system process intrinsically linked to terrestrial plant life (Mariani et al., 2016). It affects many ecosystem processes and often determines vegetation distribution (Edwards et al., 2018, Mutch, 1970, Price et al., 2015, Russell-Smith et al., 2007). It has also noted to have significant effects on biodiversity (Bird et al., 2008, Bradstock et al., 2012, Russell-Smith et al., 2007). The distribution of quantities of Australia's biota, as well as plant adaptations (e.g. serotiny and resprouting), have been attributed to recurrent patterns of fire (Russell-Smith et al., 2007). Mutch (1970) proposed fire-dependent plant communities to have developed flammable traits as a result of natural selection, suggesting a convergent evolution between fire regimes and plants. Bradstock et al (2012) note, however, that little evidence of this evolutionary relationship has been found within the fossil record.

Vegetation is not only a source of available fuel it may also determine fire behaviour. Bradstock (2010) notes the variability of fire occurrence, intensity and spread to be highly influenced by the dispersal of sufficient dry fuels. Many contemporary fire management strategies seek to limit the accumulation of dry fuels through hazard reduction burning in regions prone to high vegetation productivity and high intensity fire (Price et al., 2015).

Bradstock (2010) identified four key processes as drivers of Australian fire regimes, each with the ability to limit fire within the context of varied biogeographic regions. Variations in biomass growth, fuel availability to burn, fire weather and ignition sources were determined to contribute to spatial and temporal dynamics relating to fire frequency and burnt area. Arid woodlands, typically characterised by sparse woody cover with low litter bed flammability, were mostly susceptible to the biomass accumulation of herbaceous species after high rainfall events. Dry sclerophyll forest biomes producing high rates of surface litter were more likely limited by fire-weather, while moist temperate forests on the east coast of Australia were sensitive to the curing of abundant biomass that accompanies conditions of drought.

## 2.3 Influences of climate

The distribution of rainfall throughout Australia is known to vary by region as well as season, a product of local and synoptic influences relating to atmospheric circulation. The wet tropical regions of northern Australia are known to experience a regular annual cycle of high fuel growth, driven by monsoonal rains, alternating to pronounced conditions of rapid and sustained drying (Russell-Smith et al., 2003, Whitehead et al., 2008). This region is characterised by highly predictable fire seasonality (Russell-Smith et al., 2003).

Rainfall within south eastern Australia, on the other hand, is typically associated with mid-latitude storms and fronts, with periodic incursions of cut-off lows and interactions with the tropics through continental scale cloud bands (Bradstock, 2010, Risbey et al., 2009). As such, rainfall is less predictable on an annual basis. Natural fire regimes within in the cool temperate forests of southeast Australia may be generalised as relatively low frequency, yet high intensity (Bradstock, 2010, Russell-Smith et al., 2007, Williamson et al., 2016). Within NSW, there is great diversity in rainfall patterns. Summer dominant rainfall in the north and east, seasonally uniform rainfall in the south and highly variable throughout the semi-arid and arid regions in the west (Murphy and Timbal, 2008).

Luke and McArthur (1978) modelled Australian fire seasonality along a latitudinal gradient, ranging from the northern tropics to Tasmania. Fire activity was determined to dominate the north during the Austral winter, progress through subtropical and temperate regions during spring and summer, with Tasmania ultimately experiencing peak fire in autumn. Subsequent studies using satellite-based observations (e.g. Bradstock et al., 2012, Russell-Smith et al., 2007, Smith et al., 2007 Williamson et al., 2016) however, have found considerable heterogeneity of fire activity between regions of similar latitudes. Accordingly, Bradstock et al (2012) and Russell-Smith et al (2007) have argued that broad-scale models, such as that of Luke and McArthur, lack suitable sophistication and fail to accurately represent contemporary fire patterning.

A large proportion of research in Australian fire studies involve the prediction and identification of fire-weather, primarily as it relates to bushfires within the highly productive temperate forested regions of southeast Australia (Russell-Smith et al., 2007, Sharples et al., 2016). The McArthur forest fire index (FFDI) is commonly applied in such cases, indicating a rating of fire danger, as well as information on potential spread rate, spotting distance and controllability (Williamson et al., 2016). The FFDI incorporates measurements of wind speed, surface temperature, dew point and drought factor (Clarke et al., 2013). Verdon (2004) warns however, that uses of the index and other similar indices of fire weather, estimates the potential for fire and should not be considered a measurement of fire activity.

Utilising the FFDI, Bradstock (2010) found responses to projections of climate change to be unique to biogeographic regions. However, the author acknowledges the complexity and uncertainty involved with the prediction of future trends, particularly in light of potential feedback mechanisms and the impact of drought tolerant exotic herbs. Interestingly, he speculates that a drying trend is likely to result in decreased burnt area for much of arid Australia, with surviving temperate forested areas more likely to be more susceptible to fire weather.

The main drivers of climate variability in southeast Australia are known to have complex spatial and temporal characteristics, which lead to a range of seasonal and geographical influences. The El Niño Southern Oscillation (ENSO) is considered the strongest influence on climatic variability within eastern Australia, determining the majority of moisture and temperature variability within the region, (Kiem and Franks, 2004, Mariani et al., 2016, Power et al., 1999, Risbey et al., 2009).

The warm phase of ENSO, El Niño, is generally accepted to associate with reduced rainfall and the promotion of drought conditions for much of southeast Australia (Mariani et al., 2016). The influence on rainfall in this region is most evident in the winter and spring months (Risbey et al., 2009). Such influences have been found to differ in extent and magnitude within the region. Despite relatively lower frequencies of high fire-risk ratings in coastal NSW, Verdon (2004) identified the influence of El Niño on fire-weather to be stronger in the southeast corner of NSW while considerably weaker in the west of the state. Western regions were determined to experience more frequent and more intense fire-weather conditions regardless of phase, yet displayed only minor increases during El Niño years.

Mariani et al (2016) conducted a study relating to observed fire in the temperate regions of southeast Australia. A significant negative relationship between the Southern Oscillation Index (SOI) and fire frequency was identified, displaying a lagged response of fire activity within the preceding year. Strong positive correlations between the SOI and rainfall were noted for much of the region in the winter (JJA) and spring (SON). However, this was not the case in the north east region, where the correlation was weaker in JJA and SON, yet stronger in Summer (DJF). This may possibly relate to the summer dominant rainfall conditions in northern and eastern NSW. Mariani et al (2018) determined NINO3.4 to be significantly correlated with both the number of fires and burnt area in temperate forests biomes of southeast Australia, adding that significant associations existed in summer between ENSO and known lightning-ignited fires.

The Inter-decadal Pacific Oscillation (IPO) is a longer-term pattern of Pacific Ocean sea surface temperature (SST) variability, with phases persisting for multiple decades. It has known to modulate the strength and nature of the ENSO cycle leading to multi-decadal patterns of wet or dry activity (Power et al., 1999). Verdon et al (2004) observed the negative phase of the IPO to influence the severity of individual ENSO events, increasing the risk of fire-danger in NSW, when associated with El Niño events.

The Indian Ocean Dipole (IOD) is another measure of SST variability, though as the name suggests, it is derived from the tropical waters of the East and West Indian Ocean. The positive IOD phase is associated with reduced transfer of moisture from the northwest of the continent to the southeast (Cai et al., 2009.). Correlations with Australian rainfall have been observed to peak between June and October (Risby et al., 2009).

Mariani et al (2016) found significant positive correlations between the IOD and natural fire activity across Australian temperate regions during SON. They argued the positive mode of the IOD preconditions bushfire activity in southeast Australia during SON and DJF, by exacerbating warm and dry conditions as well as increasing dry fuel load. Yet much of the analysis was focused on effects within the state of Victoria. Concluding that its influence on bushfire events within Victoria was greater than that of ENSO.

The Southern Annular Mode (SAM) is the dominant mode of climate variability in the southern hemisphere, however its impacts are often less apparent in lower latitudes (Ho et al., 2012). It displays significant daily and monthly variability (Hendon et al., 2007) and is derived from atmospheric observations of geopotential height or mean sea level pressure (Marshall, 2003). The positive mode of the SAM has been linked to low winter rainfall and periods of protracted droughts within southwestern WA and southeast Australia (Hendon et al., 2007, Ho et al., 2012). Yet studies have shown positive correlations with summer rainfall over coastal NSW (Hendon et al., 2007).

Mariani et al (2018) observed high partial correlations between the SAM and spring and summer fire activity throughout the temperate regions of the southern hemisphere, noting that southeast Australia did not display a significant correlation with lightning lit fires. Mariani et al (2016) also tested the SAM and IOD and found no significant relationship from each with observed fire. The authors note that a possible explanation for this divergence could lie in the finding that much of the occurrence of fire within southeast Australia is linked to ignitions.

## 2.4 Human influences

### 2.4.1 Pre-European

Humans have primarily been considered as potential sources of ignitions (Bradstock, 2010, Russell-Smith et al., 2007) and as such have made significant changes to the timing, frequency, spread and intensity of fires (Bradstock et al., 2012). The selective and progressive use of fire by people is likely to have modified Australian vegetation, influenced processes of erosion and potentially contributed to aridity over thousands of years (Bradstock et al., 2012, Latz, 1995). Bradstock et al (2012) warn however, that the palaeo-fire record provides little support for large-scale impacts of human activity on Australasian fire regimes.

Latz (1995) observed that fire has traditionally been used by Aboriginal peoples to aid hunting and cooking, to encourage useful plants and to provide warmth as well as signal their presence to others. The introduction of seasonal patch burning, frequently utilised for the creation and maintenance of grazing land, is likely to have resulted in a fine-grained mosaic of burnt and revegetating habitat. This patchiness is thought to have altered the spread of fire across the continent while limiting fire intensity by the reducing accumulated fuel loads.

Habitat heterogeneity from Aboriginal fire management has been linked to greater biotic diversity or 'pyrodiversity' (Bird et al., 2008, Bradstock et al., 2012, Latz, 1995). Furthermore, it is considered highly influential in the survival of many species of plants and animals observed to be undergoing population decline following the broad scale breakdown of the practice (Bradstock et al., 2012).

### 2.4.2 Post-European

This established system of Aboriginal fire management, according to Latz (1995), was disrupted by European arrival, through both settler resistance to fire and the modification of vegetation from the introduction of feral and domestic animals. Bradstock et al (2012) further suggest that European settlers brought with them new attitudes to fire and fragmentation, further modifying the landscape with clearing associated with property ownership and land uses relating to agriculture.

Land use changed dramatically.  Currently grazing accounts for more than half of Australia's land use (abs.gov.au, 2018), followed by the 'minimally used' protected and nature conservation areas amounting to the majority of the remainder (ABARES, 2016). The highly fragmented semi-arid to coastal cropping zones, by comparison, amounts to as little as 3.72% of Australia's land use (ABARES, 2016).

While fire is synonymous with the tropical savannah region of northern Australia, Russel-Smith et al (2007) found no significant association between fire incidence and land use in this region, because of the broad range of land management practices within the region. Whilst lightning strikes drive fires, most ignition sources were considered to be mostly of human origin. In contrast, the cropping industry has a clear management regime which includes fire. After harvest, sowing and tillage operations for subsequent crops may be inhibited by the physical obstruction of machinery by stubble (Sidhu et al., 2007, Smith et al., 2007). Some straw is undesirable as a grazing product, for example rice, due to the high silica content (Sidhu et al, 2007). As a result, stubble is frequently burnt as a low-cost and immediate solution to waste management (Korontzi, 2005), thereby avoiding additional expenses relating to the purchase or modification of existing machinery (Sidhu et al., 2007). Further motivations for stubble burning may include the management of disease (Lanoiselet et al., 2005) weeds (Walsh and Newman, 2007) and pests, as well as protection from frosts (Vermeire et al., 2005).

Lanoiselet et al (2005) argues that many crop diseases have been found to carry over in stubble-retained continuous cropping systems and advocates the use of stubble burning as a treatment. The authors emphasise the need for fire use in rice growing regions, as fungicides are not registered for the control of rice diseases in Australia. Sweetingham et al (1993), on the other hand, suggest retained stubble mulch may limit the spread of rainfall-splash distributed diseases as protective cover. The burning of residual stubble may also eradicate emergent weeds with minimal herbicide use (Smith et al., 2007). Conservation farming practices, including stubble retention have been broadly implicated as contributors to increasing herbicide resistance in weeds, including ryegrass, wild oats and wild radish (Scott et al., 2010, Smith et al., 2007). However, Walsh and Newman (2007) argue the intensity of burn to be integral in the efficacy of fire as a treatment.

Very few published studies offer insight into the distribution of stubble burning within Australia, let alone NSW, highlighting a substantial knowledge gap with regards to managed fire use. Foremost was the satellite-derived investigation of observed burning by Smith et al (2007), whereby MODIS detected fire hotspots, relating to agricultural activities in southwest Australia, were analysed and compared with a farm survey to estimate burnt area relating to cropping. In another study, Scott et al (2010) review various stubble management surveys, conducted throughout southern Australia, within the context of the work of Smith et al (2007) to highlight regional trends.

Smith et al (2007) found high fire densities within the cropping regions of southeast and southwest Australia in 2005, with most activity occurring between March and June. Bradstock et al (2012) also noted areas within the southeast and southwest of the continent to display fire activity peaking in the autumn months, coincident with agricultural waste burning. Smith et al (2007) found wheat to be the most frequently burnt crop in southwest WA, followed by canola, barley, lupins, oats and grasses. Scott et al (2010), speculated that cropping regions in central and southern NSW, VIC and SA were likely to display similar patterns, acknowledging that no data currently existed to support their claim.

Scott et al (2010), found various differences in reported stubble management practices between states. While the conservation of moisture was a primary driver of stubble retention in all states, WA and QLD were determined to favour higher rates of stubble retention compared to other states due to concerns of soil erosion from wind and rain. The authors note that stubble burning had effectively been abandoned in QLD, where the decomposition rates of incorporated stubble are shown to be higher.

Sowing within stubble, by direct drilling, was common in both WA and northern VIC, while VIC and NSW displayed higher rates of stubble burning when compared to all other states. Scott et al (2010) attribute much of this irregularity to selective application of conservation farming practices in different regions. Whereby tillage may be reduced in some areas, yet stubble removed by burning. In other areas, stubble may be retained, yet ploughed into the soil.

Much of the disparity in practices appears to be related to conditions of soil, geomorphology and climate. Scott et al (2010) highlight this as they observe that problems and benefits associated with stubble retention vary by crop, season, soil type and region.

However, there is also some suggestion of delineation between state boundaries, which may indicate cultural or administrative influences.

Within NSW, the central and southern regions were identified by Scott et al (2010) as areas with comparatively lower rates of stubble retention. The primary reason given for stubble removal by farmers within these regions was the obstruction to sowing from high stubble loads, in part owing to the relatively high rainfall experienced in this region. Cropping areas within the drier regions of western NSW were shown to conduct less frequent burns (Scott et al., 2010).

Scott et al. (2010), found that the majority of respondents to a southern NSW postal survey reported grazing as the principal form of stubble management, followed by stubble burning. This appears consistent with the wheat/sheep mixed strategy associated with the Southeast Australian wheat belt. However, as Sidhu et al (2007) had noted, the nutrient and protein content is limited. Robertson, 2002 remarks the quality of wheat stubble grazed in southern Australia was low and deteriorated over summer.

Scott et al (2010) also determined burning to be less common in northern NSW, which apparently displayed practices more in common to those of QLD, including a preference to burn over summer. Seasonal timing of stubble burning displays a degree of regional variability, which may be useful for the detection and identification of such activities. According to Scott et al (2010), autumn burning is commonly practiced throughout much of southern Australia, prior to the sowing of a winter wheat crop. Summer burns were found to be common practice in northern NSW, directly after harvest.

This regional divergence in the timing of burns has been attributed to the benefits of stubble retention over the summer season (Scott et al, 2010). Soil moisture is conserved, primarily through increased infiltration, but also reduced evaporation (Scott et al, 2010). Furthermore, the risk of erosion from high intensity summer rainfall events is reduced (Scott et al., 2010, Yu and Rosewell, 1996), suggesting that both spatial and temporal variations in stubble management may not only be influenced by cultural and administrative differences, but also regional climate.

## 2.5 Fire Detection

The Moderate Resolution Imaging Spectrometer (MODIS) MOD14 active fire detection product is currently considered the most developed and widely used dataset for fire point detections (Hantson et al., 2013, Schroeder et al., 2014). Improvements to spectral, temporal and temporal resolutions, geolocation and orbit stability, as well as increases of thermal channels and sensitivities, distinguish the MODIS array from prior satellite sensors (Korontzi, 2005). As a component of NASA Earth Observation System, it was the first purpose-built global fire detection instrument (Korontzi, 2005), offering daily observations and stage three validation (Hantson et al., 2013). The dataset offers a reliable and comprehensive coverage of fire activity in both spatial and temporal aspects with low overall commission errors. (Hantson et al., 2013)

Fire detection points, or hotspots, represent the centre of a thermal anomaly sensor pixel (Hantson et al., 2013). Each pixel represents an area of $1km^2$ at nadir and the mid thermal infrared signature is compared with surrounding thermal pixels (Smith, 2007). A fire may reside anywhere within the individual pixel however, and multiple fires within a single pixel cannot be distinguished (Hantson et al., 2013, Korontzi et al., 2008). The MODIS sensor array consists of two sun-synchronous satellites consisting of Terra, launched in 1999 and Aqua, launched in 2002. The combination two daily equatorial passes each of the Terra and Aqua satellites result full global coverage every 12 hours (Giglio et al., 2016). Terra makes an equatorial pass at 10:30h and 22:30h local time, Aqua at 13:30 and 22:30h local time (Hantson et al., 2013). Data losses following the launch of Terra resulted in restrictions of time series analysis to those acquired November 2000 onward. (Giglio et al., 2016, McCarty et al., 2007).

Despite the advantages of MODIS hotspot detection, limitations are inherent in its use and performance may vary according with land use cover. In a worldwide study of fire occurrence using MODIS MOD14, Hantston et al (2013) observed high omission errors associated with the detection of smaller fires (<50 ha). As little as 10-50% were detected in some regions. The authors caution that hotspot interpretation should be considered in light of a bias toward larger fires as well as variability relating to land cover.  High omission errors were commonly detected in regions with grassland and shrubland ground cover.

Smith et al (2006), in a study of fire occurrence and burnt area in West Australian agricultural regions, found considerably lower detections than anticipated, with only 13% of burns reported by farm survey successfully detected. The authors however conclude that the low rates of detection were primarily a result of the timing of satellite overpass, noting that more detections were made by Aqua during its pm overpass, relating to a clear preference of afternoon burning within the region.  Hanston et al (2013) make comparable observations regarding the timing of overpass and the inconsistency of fire activity through space and time.

Hanston et al (2013) found omissions relating to increases of dense cloud cover. However, Smith et al (2007) note cloud cover to have no significant correlation with low detection rates in their study. Furthermore, Gilglio et al. (2016) observed smoke emissions from large fires to mask the incidence of smaller fires, increasing the number of omissions. Omissions may also occur due to small gaps to complete coverage in lower latitudes ± 30˚ (Hanston et al. 2013).

Subsequent MODIS MOD14 algorithm updates have led to improvements regarding omission errors (Giglio et al., 2016), however, the effects of such improvements do not apply evenly to all land cover types. MODIS hotspot commission errors by comparison are considered to be lower than omission errors, with the latest C6 algorithm reducing overall commission errors to 1.2% (Giglio et al., 2016). In a global study, Korontzi et al. (2006) noted swath overlap in mid- and high-latitudes to have the potential to result in multiple detections of a fire instance. Further commission errors have been observed in industrial and urban areas, relating to heat-sources and reflective rooftops (Smith et al., 2007).

## 2.6 Summary

The natural occurrence of fire as well as the characteristics of fire regimes are governed by the presence of sufficient vegetation biomass accumulation, the curing or treatment of that biomass as dry fuel, weather conditions assisting with the spread of fire and sources of ignition. The modification of vegetation characteristics through clearing, fragmentation and the planting of exotic vegetation has inevitably imposed changes to naturally occurring fire regimes throughout much of Australia. The direct use of fire as a tool for land management has further influenced changes in fire activity, particularly in intensive cropping regions. A trend of rapid change in fire use within Australia has been highly pronounced post-European arrival.

The complex interdependency between fire, vegetation, climate and people results in diverse patterns of fire activity throughout the continent, sometimes conflicting with established expectations. However, the influences of climate on fire variability are predominantly stronger on larger spatial and temporal scales. Inter-annual variations of climate and localised weather conditions have direct effects on land management, however, many management practices are frequently employed to regulate the short-term effects of natural climate variability. As a result, smaller temporal and spatial resolutions of fire activity are likely more susceptible to the influence of administrative and cultural conditions.

Existing literature on fire activity within rural NSW has been found to be focused toward infrequent and unmanaged bushfire activity, as result of catastrophic incidences driving the need for research. A small amount of national satellite observations of fire density and seasonality suggest NSW to display substantial fire activity coincident with preparation for winter cropping. A clear gap in knowledge has been identified with regards to the contribution of crop residue burning to the total fire activity within NSW.

# Chapter 3: Methodology

## 3.1 Data Sources

### 3.1.1 MODIS

Fire hotspot data from the MODIS Collection 6 fire product was retrieved from the Information and Resource Management System (FIRMS) Archive Download Tool (Earthdata, 2018). Downloads were in the format of ESRI GIS point data Shapefiles, limited to the Australian Continent and conducted in monthly instalments, for the period September 2002 to November 2017. MODIS was selected over more contemporary measures, such as VIIRS, due to a greater historical framework and superior levels of validation established from numerous studies.

Despite the availability of archive data from the Terra satellite, collection was limited to September 2002 as the availability of data from the Aqua satellite commenced in July 2002 and seasonal analysis was required. Observations by Smith et al (2007) suggested a higher rate of detection in Aqua supplied data, due to greater correspondence with timing of agricultural burning practices, which was confirmed in preliminary analysis.

Point data is representative of the centroid of a $1km^2$ pixel indicating the detection of one or more thermal anomalies (Hantson et al., 2013), therefore results provided within this thesis specify the registration of detected pixels with fire, rather than unique instances of fire.

### 3.1.2 Map boundaries

Australian NRM and NSW LGA boundary files were provided by email from the NSW Office of Environment and Heritage as ESRI GIS Shapefiles. Each layer was used to provide distinct spatial resolutions of fire detection summary data and to provide area calculations for the estimation of fire frequency and density. NRM regions are representative of LLS regions within this study.

### 3.1.3 Land use fires

Both 2007 and 2013 NSW Land use captures were downloaded from the NSW government Sharing and Enabling Environmental Data (SEED) website in the format of ESRI GIS Shapefiles. The 2013 land use file represented the most current published capture at the commencement of work and was used for the majority analysis of the study period.

The previous capture, 2007 was included for the estimation of land use change within the study period. During preliminary analysis, the 2007 capture was identified as displaying less contemporaneous properties when compared with the 2013 capture and determined to be a less reliable indicator of land use within the sampling period. Consequentially its direct application to land use analysis was limited to comparisons of area between conditions of extended drought and the current period.

## 3.2 Data Processing

### 3.2.1 Geographic Information Systems

#### 3.2.1.1 Coordinate systems and layer projections

ESRI GIS Shapefiles were imported into ArcMap as layers. All layers were projected as *GCS GDA 1994* for geoprocessing, to ensure consistency with the sizable land use files and their native coordinate system. Calculations of area relating to state, NRM, LGA and land use type were conducted separately, whereby all layers were projected as *GDA 1994 New South Wales Lambert* to provide measurement accuracy in hectares.

#### 3.2.1.2 Geoprocessing

Layers of monthly MODIS fire product point data, containing temporal acquisition and spatial coordinate features, were given state and regional attributes by use of a spatial join with the Australian NRM polygon layer. New columns of month and year were derived from timestamp values. Combined layers were exported for use in national analysis (Chapter 4) before being limited to NSW by definition query. The NSW LGA and the NSW land use polygon layer were also spatially joined to the point data layer to accrue further spatial and land use attributes (Figure 3.1), before exported as monthly .csv files.

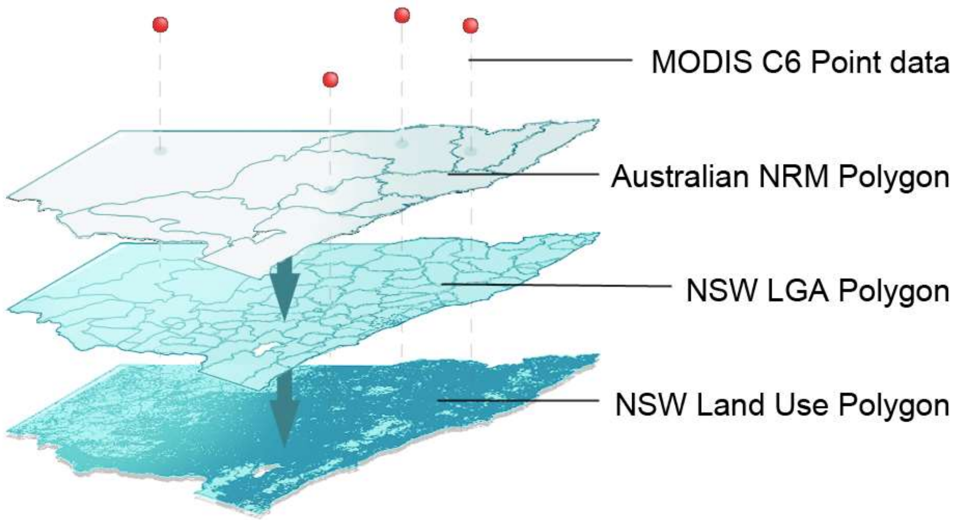


**Figure 3.1.** The stacked arrangement of spatial joins from polygon to point data, providing spatial details of administrative boundaries and land use information to fire detections.

Area measurements were performed for states, NRM regions and LGA areas, as well as NSW and Riverina land uses using calculate geometry and summary statistics. These measurements were compiled in tables for use in the calculation of fire density and fire frequency values.

Copies of monthly MODIS fire product national point data were merged into a single layer file and rasterised at a resolution of 1 cell = 1,000 ha. Rasterisation was repeated four times with data reduced by definition query to isolate months of each season. This sequence was also repeated after clipping spatial data to NSW.

### 3.2.2 Python

Monthly data from GIS exported layer datasets were compiled and concatenated within Python on account of the record volume being unsuited for spreadsheet applications. Two primary datasets were created pertaining to National and NSW level data. A series of record counts were produced based on cumulative results for on state, LLS, LGA resolutions as well as land use type, before pivot table analysis was performed on each, maintaining monthly summaries.

This was repeated for seasonal analysis with the appropriate aggregation of months into seasons for each year. Seasonal sampling ranged from SON 2002 to SON 2017. Seasons were then separated by use of Boolean functions. Pivot tables of annual detection counts were also conducted for each summary focus and mean values calculated. The annual sampling period differed from the seasonal sampling period comprising of detections over 15 years from January 2003 to December 2017. Code of the many hundreds of multi-line operations have not been included for review, though may be provided on request

### 3.2.3 Statistics

A Poisson General Linear Model was considered early in the study; however, it was found to present a substantial resource demand when considering an appropriate range of testable factors covering the spatial and temporal extents studied. Concerns regarding the failed assumption of random sampling from the timing and sensitivity of remote sensory equipment, as highlighted by Smith et al (2007), limited the use of many statistical methods. Analysis of annual means and linear regressions were presented, though emphasis is given to the identification of broader trends, calculated in Python with outliers identified and retained for analysis.

### 3.3 Limitations

This study contains investigation into the role of fire management behaviours with relation to land use. It acknowledges the complex interactions of cultural, economic, technological, and climatic factors with land management and offers only limited discussion regarding such influences. Linear analysis of climate variability and state-wide fire occurrence was conducted to indicate broad-level trends of interactivity however the author concedes the inherent nonlinear nature of climate processes cannot be truly reflected within such analysis. It highlights conflicting responses of land management between land uses and is not intended to be comprehensive representation of climate-fire dynamics.

Dynamic change in land use is also a source of concern, particularly within in agricultural regions where mixed grazing and cropping practices occur. Measurements of cropping land use change between 2007 and 2013 are dependent on an array of differently scaled sources, collected over a range of acquisition periods, which limits confidence in the precise and accurate representation of land use within the sampling period.

The resolution of the MODIS sensory array is limited to a 1km$^2$ (100 ha) pixel size. Detected thermal anomalies may be present anywhere within the pixel, therefore the proximity of the point location to the source remains unknown within this area. The presence of multiple land uses within a single pixel area increases the potential for the misclassification of land use type associated with each record, thereby increasing classification uncertainty.

Sensitivity testing by a count of land uses types within a 1 km$^2$ grid size has revealed lower land use diversity and therefore greater certainty in the arid western region of NSW (Figure 3.2). Land use diversity is shown to increase approaching coastal regions, with the exception of densely forested areas. Higher levels of uncertainty are shown to associate with population centres and water courses.

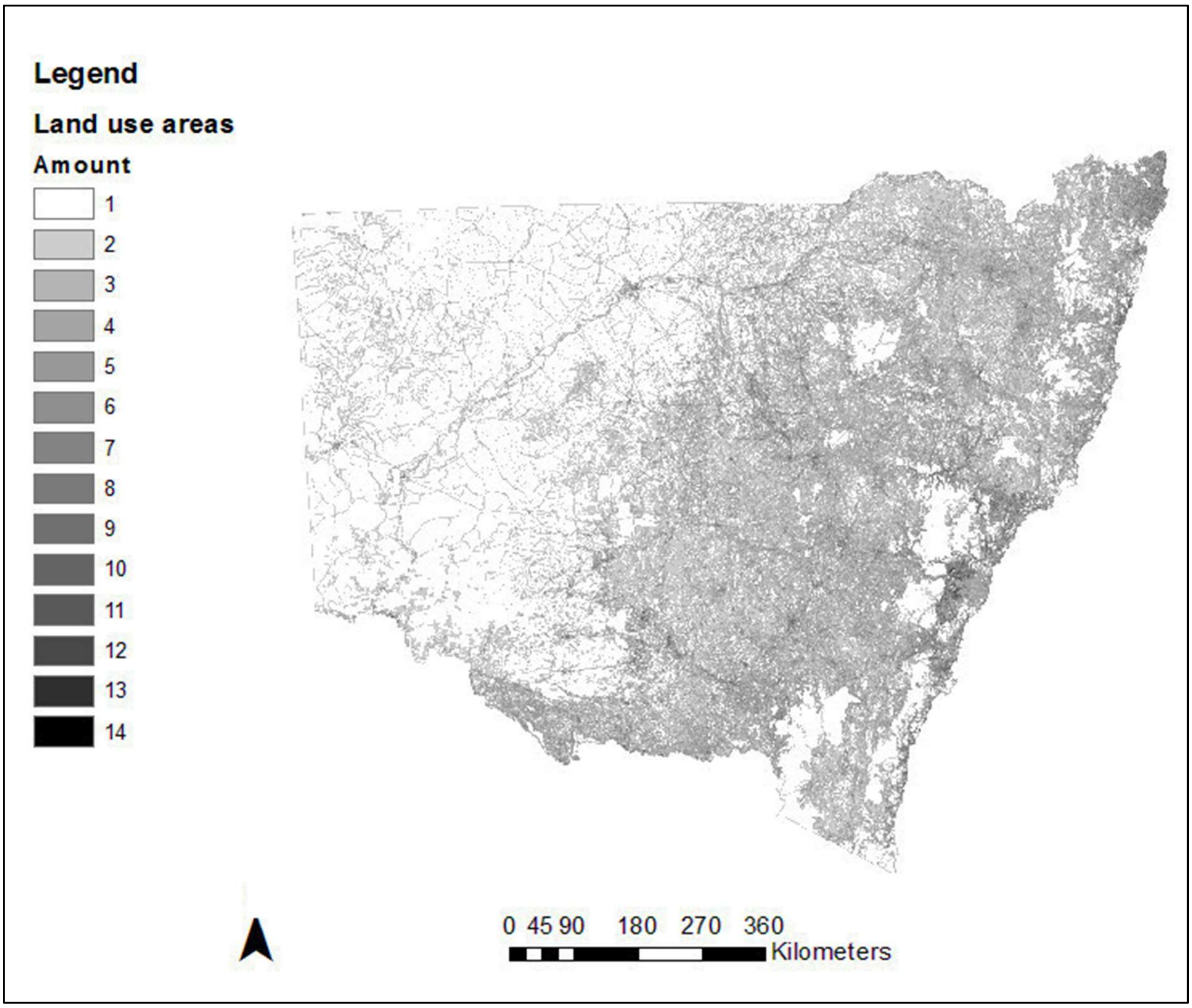


**Figure 3.2.** Land use classification uncertainty within NSW. Values denote the number of land use types within a 1km$^2$ cell. Darker regions represent greater land use heterogeneity within each cell and therefore greater uncertainty of accurate land use classification.

# Chapter 4: Fire Frequency and Seasonality at a National Scale

## 4.1 Introduction

This chapter addresses the first overall study aim; characterise the distribution and frequency of fire at a national scale to interpret state-level trends in context of climate drivers. There has been much research exploring the climate patterns, synoptic drivers, rainfall distribution across Australia (Bradstock, 2010, Russell-Smith et al., 2007, Williamson et al., 2016). Significant work has looked at broad scale latitudinal frequencies of Australian fire either using modelled data (Luke and McArthur, 1978) or measured using satellite-based observations (e.g. Bradstock et al., 2012, Russell-Smith et al., 2007, Smith et al., 2007 Williamson et al., 2016). Overwhelmingly, the literature suggest considerable heterogeneity of fire activity between regions of similar latitudes, leading to the suggestion that perhaps more than climate drivers contribute to contemporary fire patterning.

The current chapter explores the distribution and frequency of fire occurrence across the continent to identify the distribution of fire occurrence across states and most importantly the frequency of those fires. Identifying the relative magnitude of continental fire load will develop a greater understanding of the type of fire, wild, planned control fires or integrated into agricultural production systems.

## 4.2 Chapter Aims

The aims for this chapter are:

1. Does the frequency of fire in NSW differ from other states and territories?
2. Does the seasonality of fire in NSW differ from other states and territories?

## 4.3 Results

### 4.3.1 Distribution of fire throughout the Australian continent.

High concentrations of aggregated fire are visible to the north of the Australian continent (Figure 4.1) throughout the tropical savannahs (Kimberly region of WA, throughout northern NT and within the Cape York Peninsula). Followed by smaller areas within south west WA, the Yorke and Eyre Peninsulas of SA, northern and eastern regions of VIC, southern NSW and the Eastern half of Central QLD. Broad areas indicating little-to-no detected fire were mostly confined to the mid-west and southern regions of WA, the majority portion of SA, eastern TAS, as well as western NSW and QLD.

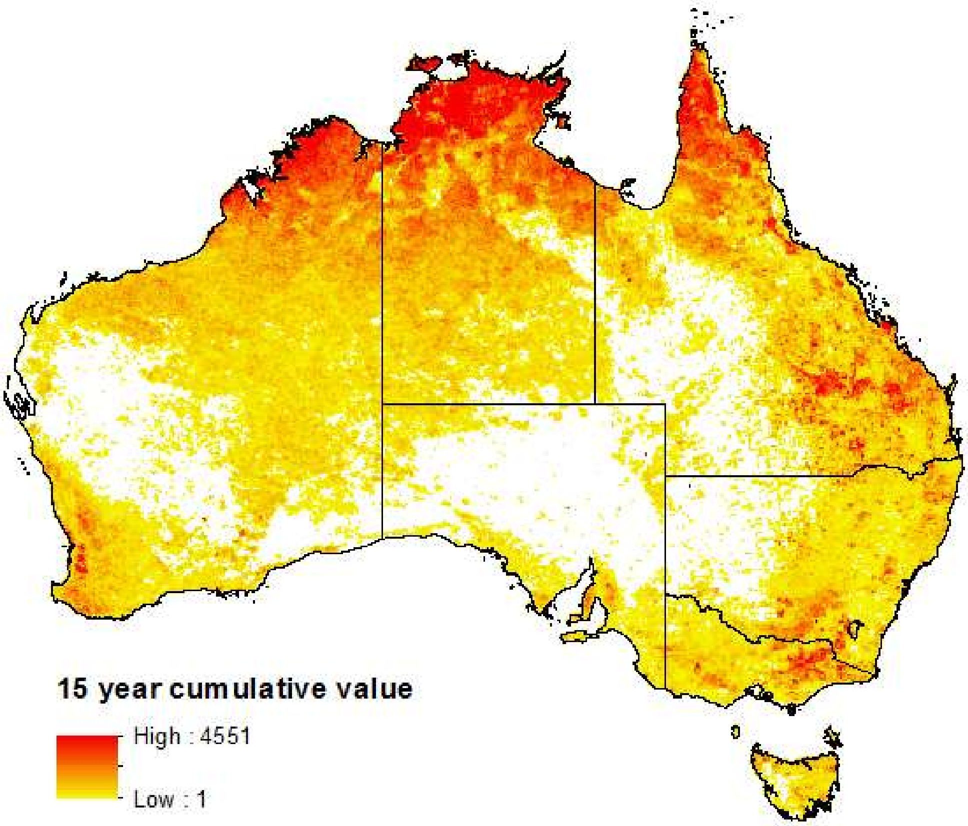


**Figure 4.1.** Aggregated national distributions of detected pixels with fire, relative to 1,000 ha cell sizes, 2003-2017.

Mean annual fire detections by state and territory similarly reflect aggregated clusters observed in the northern tropical regions. The NT recoded 94,882 pixels with fire, with WA and QLD following at 72,394 and 63,836, respectively. Of the residual states and territories, NSW recorded 13,250 mean annual detections, above VIC (7,191), SA (4,187) TAS (1,561) and the ACT (141), indicating a broad disparity between the north and south of the continent.

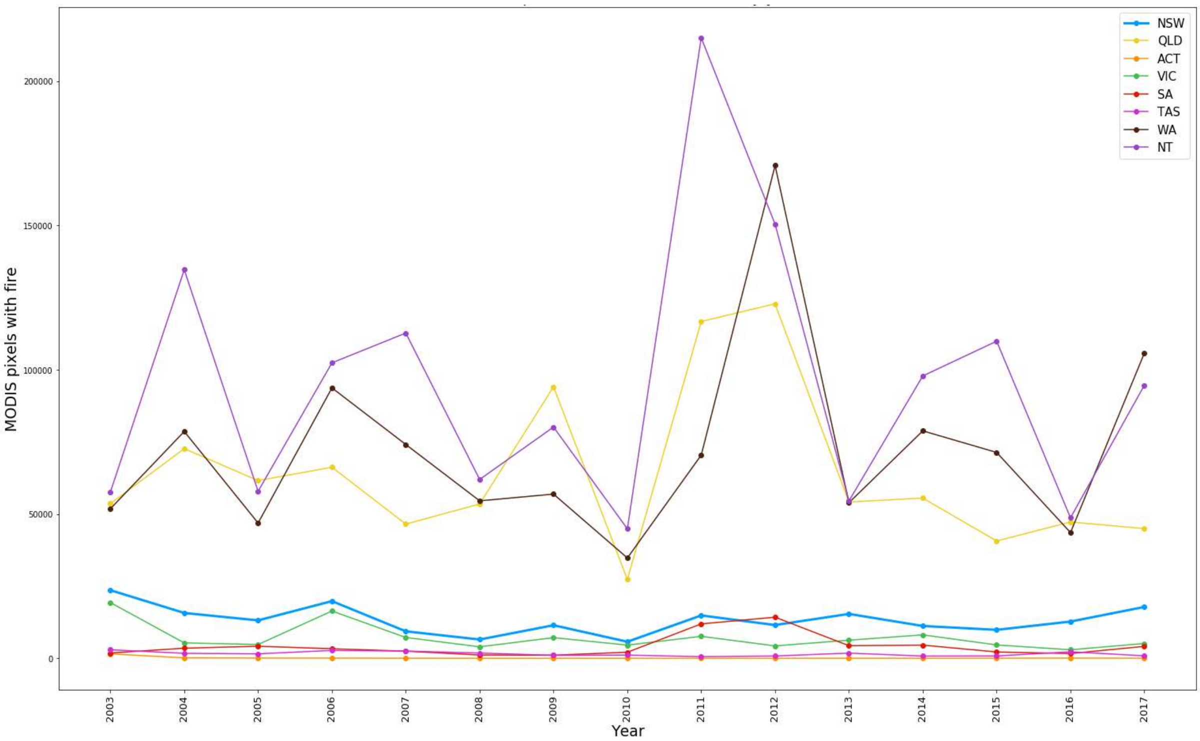


**Figure 4.2.** Time-series of annual pixels with fire by state, 2003-2017.

Northern Australia consistently was observed to have greater fire frequencies throughout the 15-year observation period (Figure 4.2). Greater inter-annual variability was pronounced in the NT, WA and QLD, with maximum values attained between 2011 and 2012. This period of heightened activity corresponded with a similar rise in SA, though was less pronounced in the remaining states and territories of southeast Australia, where maximum values were established in 2003.

NSW, VIC, ACT and TAS each displayed broadly declining trends for the duration of the study period, strongly influenced by proportionately higher levels attained between 2003 and 2006. However, after a period of lower activity between 2007 and 2010, levels of annual fire within NSW were shown to escalate between 2011 and 2017.

### 4.3.2 State-level fire frequency rankings

Consistent with total detections, the NT was observed to display the highest mean annual fire frequency values, totalling $6.634 \times 10^{-3}$ pixels with fire per ha. The ACT, occupying the smallest area, followed a distant second to the NT at $6.01 \times 10^{-4}$ pixels with fire per ha. Fire density values for QLD ($3.56 \times 10^{-4}$/ha), VIC ($3.15 \times 10^{-4}$/ha), WA ($2.80 \times 10^{-4}$/ha), and TAS ($0.000223 \times 10^{-4}$/ha) were determined to be greater than that of NSW ($1.65 \times 10^{-4}$/ha), which exhibited the second lowest ranking, above SA ($4.2 \times 10^{-5}$/ha).

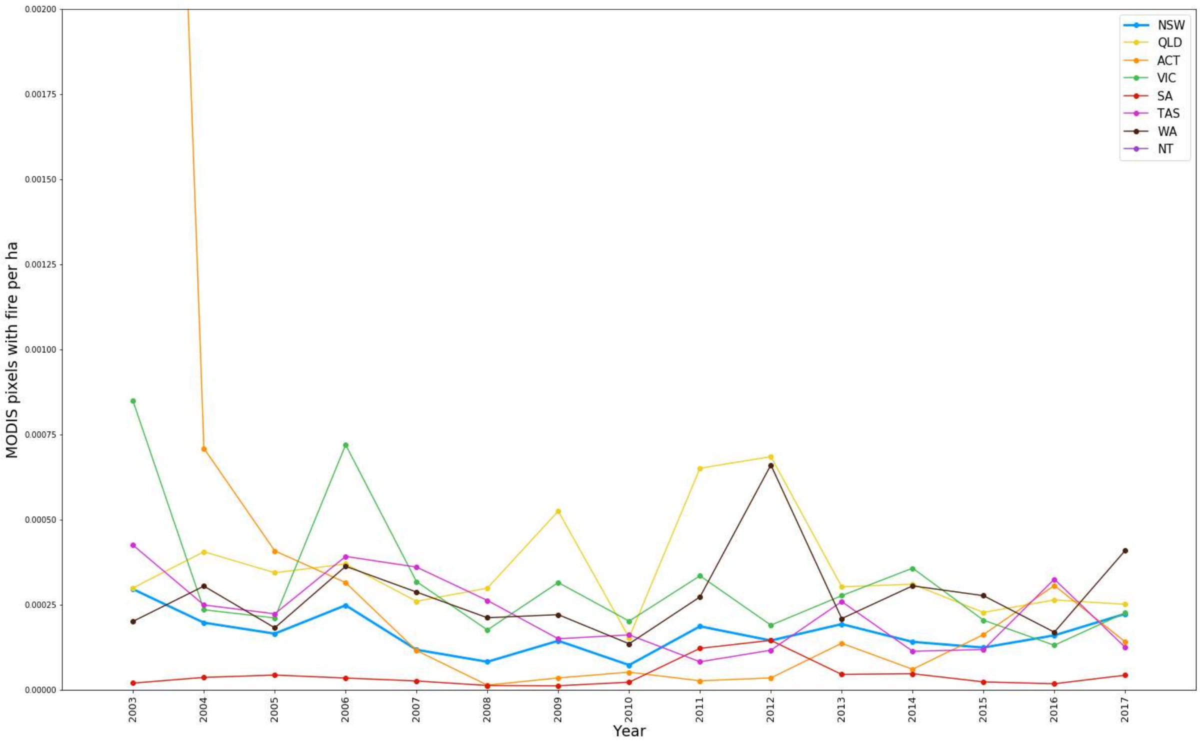


**Figure 4.3.** Annual fire density rates (per ha) of all states and territories, 2003-2017. The NT lays beyond the visible y axis (all years). ACT 2003 = $6.01 \times 10^{-4}$.

Time-series analysis reveals the Fire frequency ranking of ACT to have been influenced primarily by a high magnitude event experienced in 2003, (Figure 4.3). A similar peak was also evident in VIC, NSW and TAS. Elevated density rates within VIC, during 2003 and 2006, surpassed those of QLD and WA as well as the remaining states, including NSW. Overall, despite a higher ranking in absolute fire detections, NSW displayed relatively low annual fire frequencies.

### 4.3.3 Seasonality of fire within the Australian continent.

National fire densities during DJF were found to be predominantly concentrated within the far south-east of the continent, (Figure 4.4). A notable cluster of high-density spans from southern VIC, into the southern regions of NSW and throughout the ACT. Moderate-density activity was shown to be distributed throughout northern and eastern QLD, with lower levels scattered throughout the north-west and central regions of the continent.

During MAM (Austral autumn), heavily concentrated fire densities spanned the Kimberly and western Top End of northern Australia, with moderate to high densities also located to the south west of the continent. Another cluster was evident in southeast Australia, though positioned north-west of the cluster identified during DJF, primarily confined to southern NSW. Smaller, isolated clusters were also located within southern VIC and regions of SA surrounding the Yorke and Eyre peninsulas.

During MAM (Austral autumn), heavily concentrated fire densities spanned the Kimberly and western Top End of northern Australia, with moderate to high densities also located to the south west of the continent. Another cluster was evident in southeast Australia, though positioned north-west of the cluster identified during DJF, primarily confined to southern NSW. Smaller, isolated clusters were also located within southern VIC and regions of SA surrounding the Yorke and Eyre peninsulas.

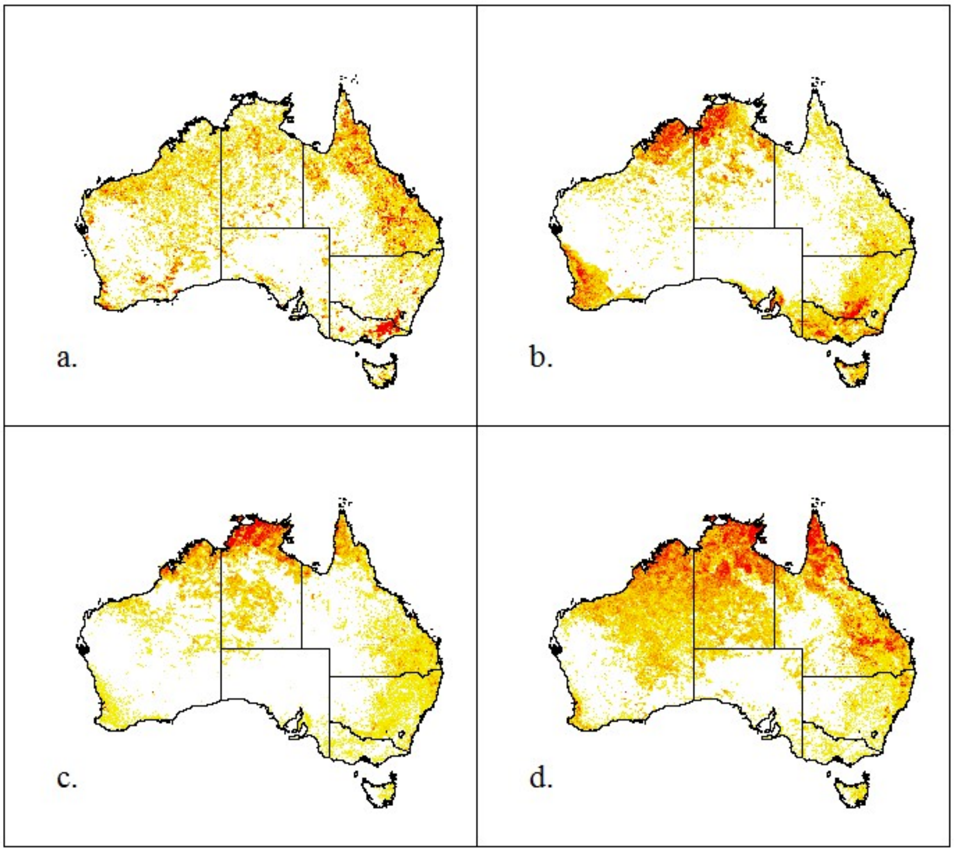


**Figure 4.4**. Seasonal distribution of accrued pixels with fire, relative to 1,000 ha cell sizes, arranged by season, **a)** DJF, **b)** MAM, **c)** JJA, and **d)** SON, for the period SON 2002 to SON 2017.

During JJA (Austral winter), highest fire densities occurred throughout the far north of the continent. Particularly throughout the tropical savannahs (NT, Kimberley in WA and Cape York QLD). Low levels of fire density were observed throughout the southern winter.

During SON (Austral spring), highest fire densities occurred again throughout the far north of the continent. Particularly throughout the tropical savannahs (NT, Kimberley in WA and Cape York QLD). Spring heralds widespread and abundant burning throughout the tropical savannahs. Fragmented clusters to the east of Northern and Central QLD indicated increased seasonal activity, as did isolated clusters detected within northern and central regions of the east coast of NSW.

The NT, WA and QLD recorded the majority of fire detection instances during SON, counter-seasonal to many of the southern states, as seen in Figure 4.5. However, each region displayed unique seasonal distributions of fire activity. WA was found to have a bimodal distribution with a secondary peak in MAM, while QLD was found to display its lowest levels of activity during the same season. The NT recorded staggered progression from DJF to SON. Lower levels of fire activity were predominantly associated with DJF in the NT and WA however, this was not the case with QLD which frequently experienced proportionately greater DJF activity than the NT and WA. Instead, low activity in QLD frequently occurred later, during MAM.

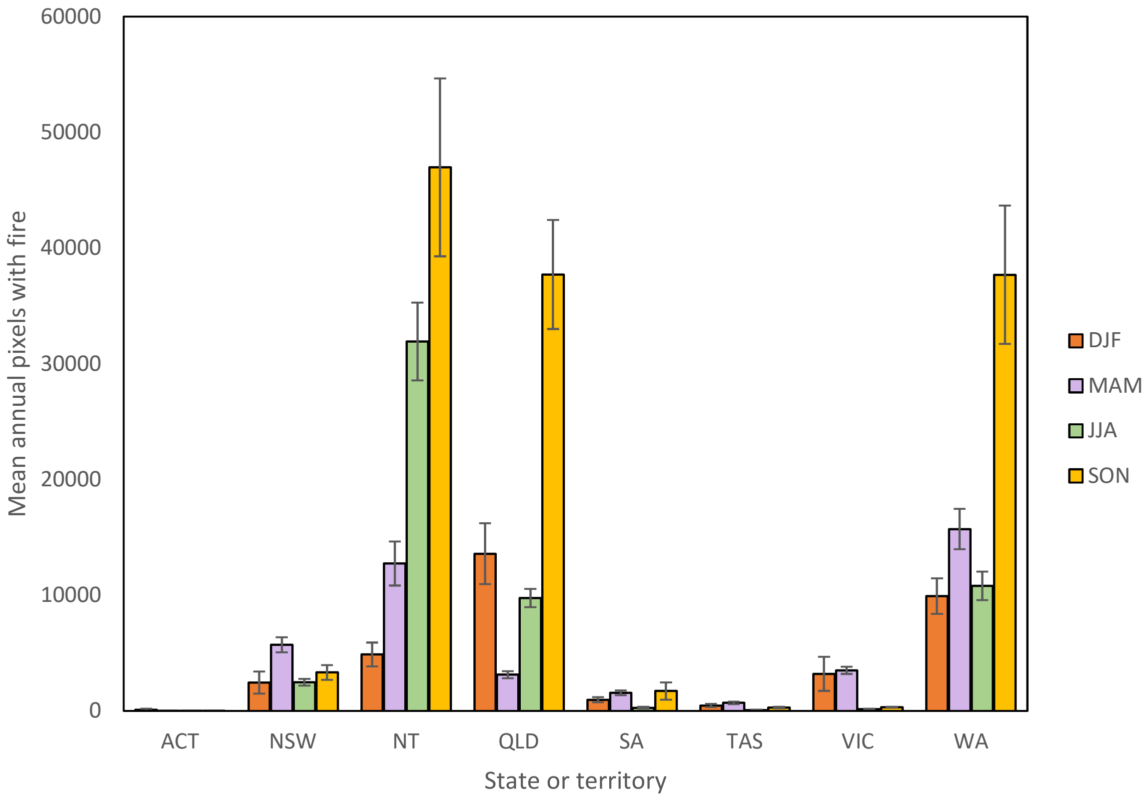


**Figure 4.5.** Mean annual pixels with fire for each of the Australian states and territories, arranged by season. SON 2002 to SON 2017.

Maximum mean fire activity within the southern states and the ACT was found to occur during MAM, with the exception of SA, which recorded greater activity in SON. The season of lowest activity was JJA in VIC, SA, TAS and the ACT, but not in the case of NSW, which displayed marginally lower rates in DJF.

Despite the prevalence of peak fire activity during SON in the north, exceptions occurred in the NT on four years, where JJA activity exceeded that of SON, as seen in Figure 4.6. Secondary peaks of MAM activity in WA was shown to be consistent and not influenced by isolated events.

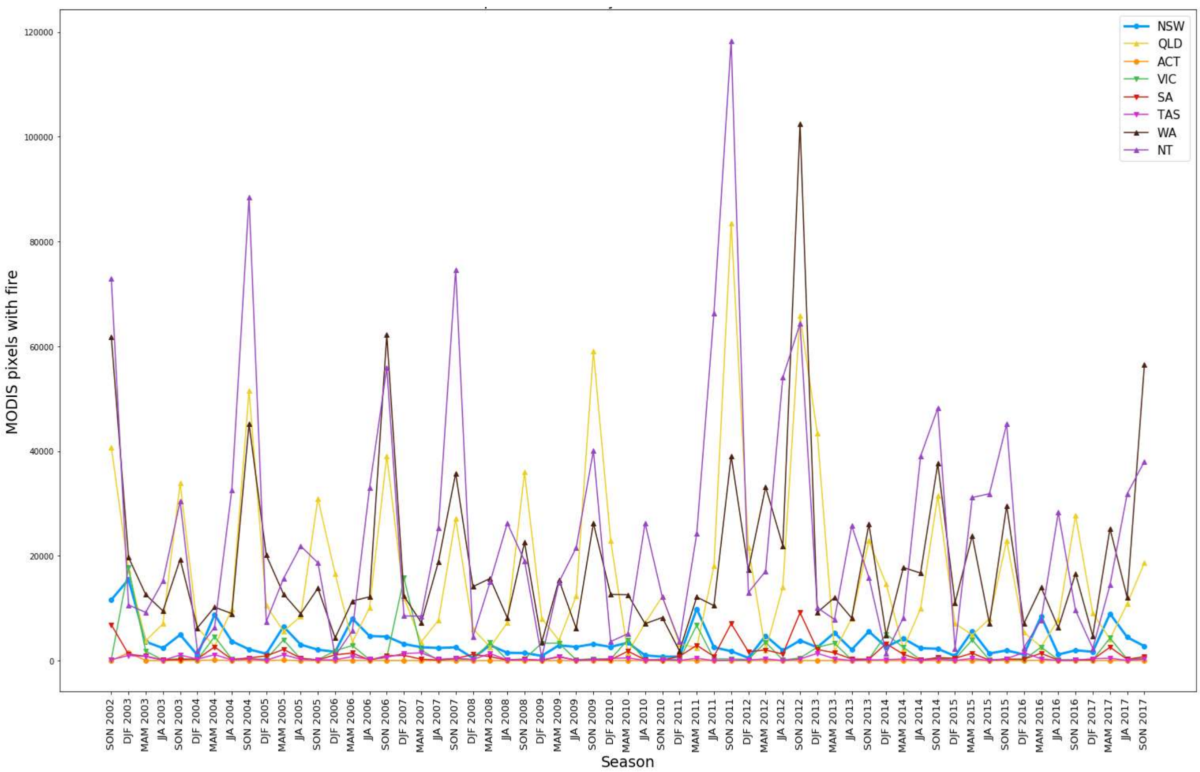


**Figure 4.6.** Time series of MODIS fire detections for Australian states and territories SON 2002-SON 2017.

NSW, VIC, SA, TAS and the ACT displayed frequent peak activity during MAM, with exceptions occurring in all states and territories during either SON or DJF, the most evident during DJF 2002-2003, or SON 2002 in the case of VIC. Within NSW, exceptions occurred during DJF 2002-2003, SON 2010 and SON 2013. Reduced activity occurred more frequently in DJF than JJA. However, the contrast between peak and baseline activity was reduced between 2006 and 2011.

Seasonal density values for VIC were frequently higher than NSW in MAM and DJF, but typically lower in other seasons, seen in Figure 4.7. The ACT recorded higher densities than NSW in MAM between 2002 and 2007, before a reversing in a lull that lasted until 2013. TAS recorded higher densities than NSW in MAM, but also in DJF for the years 2007 2010, 2013, and 2016. SA sustained lower densities than NSW in all seasons, with the exception of SON 2011 and 2012.

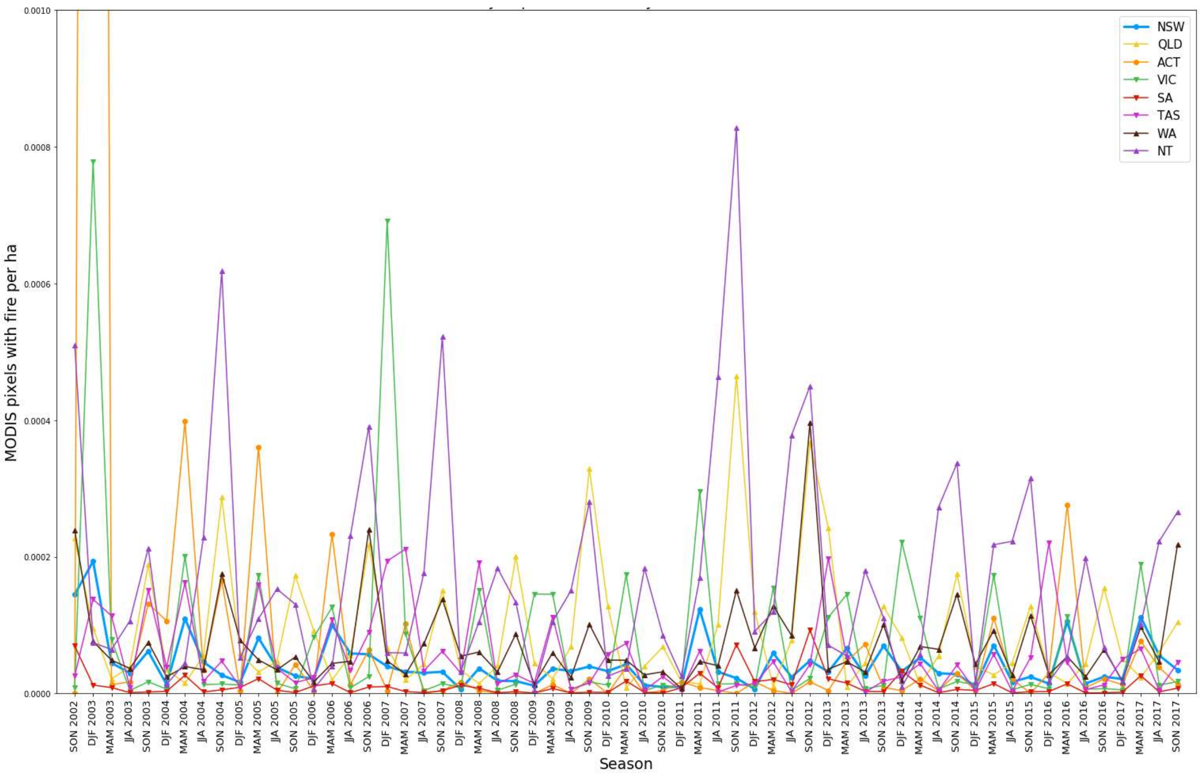


**Figure 4.7.** Seasonal fire density rates (per ha) of Australian states and territories, SON 2002-SON 2017.

## 4.4 Discussion

The frequency and distribution of fire is notably uneven between Australian states and territories. Spatial analysis of national fire densities suggest climate, particularly rainfall, to be the dominant diver of fire operating on a continental scale. Broad-scale patterns of distribution and seasonality align with the findings of Russel Smith et al, (2007), who observed rainfall seasonality to be the primary determinant of fire patterning in Australia during a study between 1997 and 2005.

The detection of extensive fire densities concentrated to the north of the continent is consistent with annual burning within the savannah biomes of the NT, WA and QLD, as documented by Yibarbuk et al (2001), Russell-Smith et al (2003), Russell-Smith et al (2007), Whitehead et al (2008), and Maier et al., (2013).

A regular annual cycle of high fuel growth, driven by monsoonal rains, alternating to pronounced conditions of rapid and sustained drying, are known to result in fire prone conditions across much of the tropical savannah and grasslands during the northern dry season and early wet, (Maier et al., 2013, Whitehead et al., 2008). Subsequently, a reduction of fire density follows the gradient of rainfall from the northern coast toward the arid interior of the continent (Maier et al., 2013).

The distribution of the more sparsely vegetated arid regions varies remarkably between Australian states and territories. The ACT, VIC and TAS are smaller in area than NSW and SA with the majority proportion receiving regular rainfall in excess of 300mm annually. SA and NSW by comparison encompass vast arid areas characterised by lower rainfall, where fire is less common (limiting the spread of fire), substantially contributing to their low state-wide fire density rankings.

Regions typified by low mean annual rainfall are, however, periodically subject to high rainfall events. This was highlighted by the peaks of fire activity in the NT, QLD and

SA directly following the strong 2010-2011 La Niña. Widespread rains had fallen in otherwise dry regions throughout northern and central Australia, including northern SA, (refer Appendix A, Figure A1). This led to increases in the production of grassy fuel and ultimately the extent of burning throughout the dry seasons (Russell-Smith et al., 2007). Extended dry conditions, particularly in WA, resulting in delayed fire activity within WA during SON 2012 (Russell-Smith et al., 2007).

Fire activity within southeast Australia was dominated by the feature of the Southeast Australian Bushfires of 2002-2003, including the devastating Canberra Bushfires, apparent in Figure 4.4a. Approximately 20,000 $km^2$ was burnt, consisting primarily of forest and grazing land, spanning from southern VIC to southern NSW and the ACT (Russell-smith et al, 2007). This event was associated with substantial rainfall deficiencies throughout southeast Australia during the 2002-2003 period (refer Appendix A, Figure A2) and conditions of extreme fire danger in DJF (Russell-smith et al, 2007).

The 2006-2007 period also saw rainfall deficiencies in southeast Australia, though not to the extent of 2002-2003, (refer Appendix A, Figure A3). Escalated fire activity within this period was more apparent in VIC than NSW due to extensive and continuous burning within the Victorian Alps and Gippsland throughout the period. Overall, DJF fire activity displayed low inter-annual frequency, associated with incidents of bushfire in NSW, and other southeast Australian states.

By contrast, the concentration of fire within southeast Australia during MAM, as seen in Figure 4b, was not influenced by isolated events of scale. Instead, fire activity during MAM, particularly within southern states, displayed a high degree of seasonal regularity with declines progressively apparent within the latter stages of the Millennium Drought.

Within WA, burning in MAM was concentrated within the extremes of two distinct geographical regions, the tropical savannah rangelands of the far north and the subtropical and temperate regions of southwest. Hazard reduction burning, to reduce the intensity and spread of late dry season fire, is practiced in the rangelands of the Kimberly region of WA, as well as the western half of the Top End of the NT. The timing of early burns during MAM, however, is not conducive to pasture productivity as subsequent growth is limited without seasonal rain. As a result, burning is frequently delayed until later in the dry season.

The distribution of fire within the continent in JJA was predominantly focused in the Top End of the NT. Activity in the region is attributable to continued cool-season hazard reduction burning. In contrast, much of southern Australia is typified by winter dominant rainfall distributions and subsequently displayed little indication of active burning. Marginally lower DJF fire activity in NSW distinguished the state from VIC, SA, TAS and the ACT and is likely to be a product of multiple seasonal rainfall distributions in separate geographical locations.

SON marked peak fire activity in the savanna and grasslands of the north, before the onset of monsoonal rains. Activity was shown to extend throughout forested regions of central QLD and into northern NSW, consistent with established models.

## 4.5 Summary

Despite periodic episodes of intense wildfire associated with conditions of drought, the frequency and coverage of fire in NSW is overshadowed by the regular seasonal burning common to the tropical savannas of the north. Total fire estimates place NSW above southern states, however, this is not reflected in fire density values as the spread of fire is limited in the sparsely vegetated western half of the state.

Seasonality of fire in NSW, while sharing many similarities, varies from other southern states and territories, possibly due to climatic influences shaping a range of rainfall regimes within its expanse. The influence of land use in NSW fire seasonality, particularly in agricultural regions, is apparent, though poorly understood.

The drivers of a positive trend in fire activity post 2010, unique to NSW, are so far unexplained. The subsequent chapter will investigate the distribution and timing of fire activity within NSW in order to isolate this apparent trend, as well as examine major climate influences to seasonal and inter-annual variability within the state.

# Chapter 5: Fire Distribution and Frequency within NSW

## 5.1 Introduction

The previous chapter explored the distribution and frequency of fire between the states and territories of the Australian continent. It established the majority of fire to occur within the tropical north, a product of climate driven contrasts in seasonal rainfall. Of the remaining states, NSW displayed the highest rates of fire detection, primarily during autumn (MAM).

This chapter explores the distribution and frequency of fire occurrence within NSW, relative to the Local Land Service regions (LLS) that comprise the states natural resource management delivery structures. The objectives of the chapter are to identify regions associated with elevated fire activity, investigate possible climate influences, including the El Niño Southern Oscillation (ENSO) and explore broader patterns of fire activity within the state.

## 5.2 Chapter Aims

The aims developed to address the objectives of this chapter are:

1. Where are fires occurring within NSW?
2. When are fires occurring within NSW?
3. What climatic factors influence the seasonality of fire in NSW?
4. Does ENSO drive the frequency of fire occurrence in NSW?

## 5.3 Results

### 5.3.1 Distribution of fire in NSW

Patterns in the frequency and distribution of detected fire throughout the LLS regions of NSW reveal a clear deficit in the west of the state, with patches of high incidence detections scattered mostly to the northeast and south of the state (Figure 5.1). Dense clustering was pronounced in the Riverina and Murray LLS region, but also zones along the higher rainfall areas in South East NSW and North Coast regions.

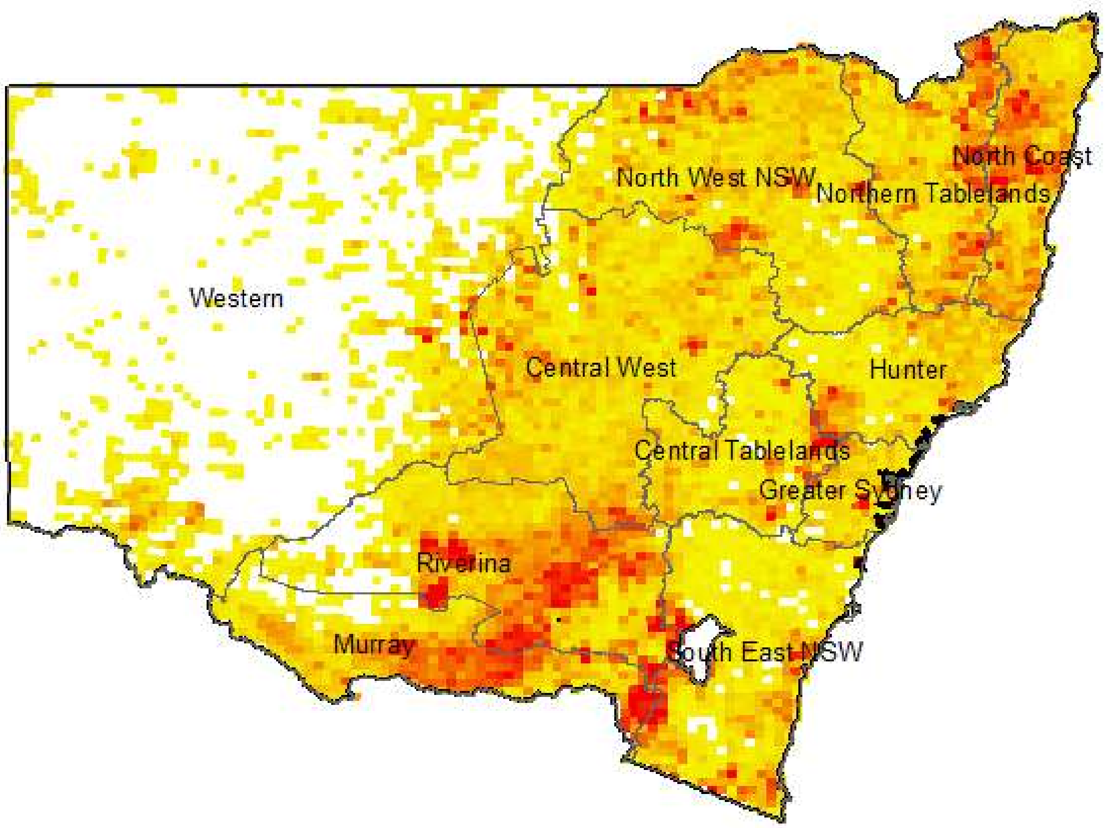


**Figure 5.1.** A map displaying the distribution of pixels, relative to 1,000 ha cell sizes, NSW LLS regions, 2003-2017.

Minor clusters were identified in Central Tablelands, Hunter and Greater Sydney regions. Moderate to low level frequencies covered the majority of area outside of the Western LLS, with exceptions occurring in the western extent of the Riverina and northern parts of the Murray LLS regions.

### 5.3.2 Mean annual detection rates of fire.

The Riverina LLS region recorded the greatest mean annual number of pixels with fire (2539) for the period 2003 to 2017. The Central West and North West of NSW followed with 1712 and 1604 respectively, suggesting a disparity of magnitude from that of the Riverina. South East NSW, Murray, North Coast and the Northern Tablelands each recorded 1422, 1433, 1194, 1192 respectively, suggesting possible trends in latitude and coastal proximity. The Western region recorded 737, preceding the near-coastal central regions of Hunter (605), Central Tablelands (543) and Greater Sydney (264).

### 5.3.3 Seasonality of total detected fire

The seasonal distribution of detected fire revealed the Riverina to have the strongest seasonal association of all NSW LLS regions, with 76% of all detections occurring during MAM (Table 5.1). Similarly, the Murray and Central West recorded greater than 50% of annual detections during MAM. Higher MAM detections were also apparent in the Central tablelands and to a lesser degree, North West and Western NSW, however overall seasonality was less defined, due to a greater spread between seasons.

In contrast, the northern and central near-coastal regions of Greater Sydney, Hunter, Northern Tablelands and the North Coast, each displayed a strong association with SON.

Detections during MAM were found to be comparatively low, however the season of lowest activity was shown to vary by region.

**Table 5.1.** Total count and percentages of total pixels with fire for each NSW LLS, arranged by season, SON 2002-SON 2017.

| LLS | DJF | MAM | JJA | SON | % DJF | % MAM | % JJA | % SON |
|---|---|---|---|---|---|---|---|---|
| **Central Tablelands** | 2,097 | 3,663 | 958 | 1,527 | 25 | 44 | 12 | 19 |
| **Central West** | 3,388 | 13,403 | 5,233 | 4,226 | 13 | 51 | 20 | 16 |
| **Greater Sydney** | 1,470 | 547 | 443 | 3,341 | 25 | 9 | 8 | 58 |
| **Hunter** | 2,021 | 1,227 | 1,655 | 6,320 | 18 | 11 | 15 | 56 |
| **Murray** | 4,058 | 14,690 | 1,634 | 1,215 | 19 | 68 | 8 | 6 |
| **North Coast** | 1,617 | 1,818 | 6,448 | 11,013 | 8 | 9 | 31 | 53 |
| **North West NSW** | 4,914 | 7,920 | 6,108 | 5,969 | 20 | 32 | 25 | 24 |
| **Northern Tablelands** | 3,104 | 2,182 | 4,195 | 11,834 | 15 | 10 | 20 | 56 |
| **Riverina** | 3,520 | 29,126 | 4,441 | 1,110 | 9 | 76 | 12 | 3 |
| **South East NSW** | 7,982 | 7,170 | 4,228 | 4,013 | 34 | 31 | 18 | 17 |
| **Western** | 2,625 | 4,061 | 1,839 | 2,706 | 23 | 36 | 16 | 24 |

### 5.3.4 Seasonal time-series: number of fires.

Time-series analysis of seasonal LLS fire detections revealed considerable inter-annual variability of seasonal amplitudes, as well as incidents of seasonal anomalies, as seen in Figure 5.2. Seasonal frequencies however, displayed a high degree of regularity. This was most evident in the Riverina LLS, which displayed recurrent high level rates of detection during MAM, with infrequent events of magnitude occurring in DJF.

Similarly to the broader state trend identified in the previous chapter, magnitudes of MAM activity were shown to be initially high in the beginning of the study period, before declining in the 2007-2010 period, peaking in 2011 and trending higher between 2015 and 2017. This pattern was also broadly represented in the Murray and Central West regions.

Despite an apparent association during DJF, as indicated by the seasonality of total fire detections, South East NSW regularly displayed peak rates of detection during MAM, with the singular exception of very-high magnitude during DJF 2002-2003. This feature of

2002-2003 was common throughout numerous LLS regions, albeit with an apparent seasonal discontinuity.

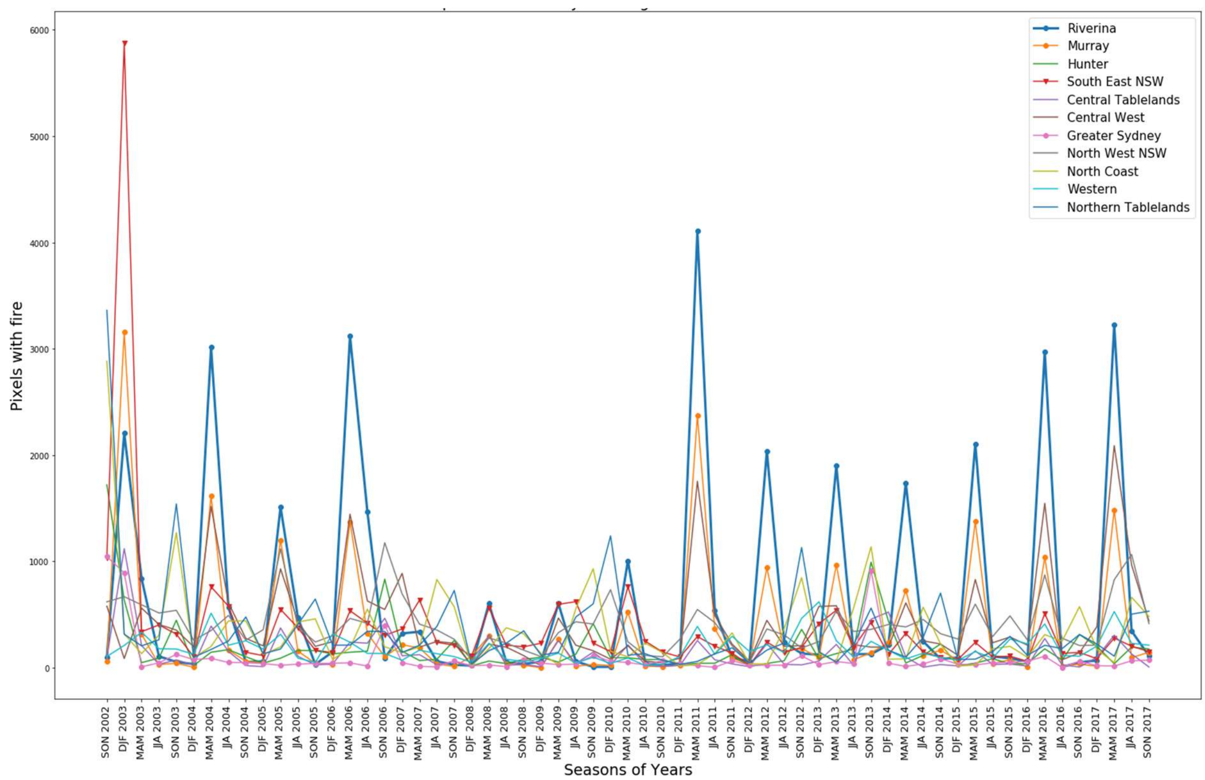


**Figure 5.2**. A seasonal time-series of recoded pixels with fire, LLS regions NSW, SON 2002-SON 2017.

Highly elevated rates of detection in the Northern Tablelands, North Coast, Hunter and Greater Sydney regions during SON 2002 preceded substantial activity in South East NSW, Murray, Riverina and the Central Tablelands in DJF 2002-2003.

The influence of this event to the annual mean seasonal values of fire detection exhibited an inversely proportional association with the extent of seasonal burning within each LLS region. The seasonal profile of South East NSW not only presented less discrete seasonal definition when compared with the Riverina, but substantially lower peak magnitudes in MAM.

### 5.3.5 Fire frequency rankings, LLS regions.

The Riverina recorded the greatest annual fire frequencies of all NSW LLSs, producing $3.79\text{x}10^{-4}$ pixels per ha ($\text{ha}^{-1}$). This result was comparable to the North Coast, which recoded $3.72\text{x}10^{-4}$/ha, followed by the Murray ($3.42\text{x}10^{-4}$/ha) and Northern Tablelands ($3.01\text{x}10^{-4}$/ha). Southeast NSW and Greater Sydney followed with $2.56\text{x}10^{-4}$/ha and $2.15\text{x}10^{-4}$/ha, respectively. North West NSW, the Central West, Hunter and Central tablelands consecutively recorded 1.94 $\text{x}10^{-4}$/ha, 1.87 $\text{x}10^{-4}$/ha, 1.84 $\text{x}10^{-4}$/ha, 1.74 $\text{x}10^{-4}$/ha, with Western NSW attaining the lowest density value of only 2.3 $\text{x}10^{-5}$/ha.

### 5.3.6 Seasonal time-series: density of fire.

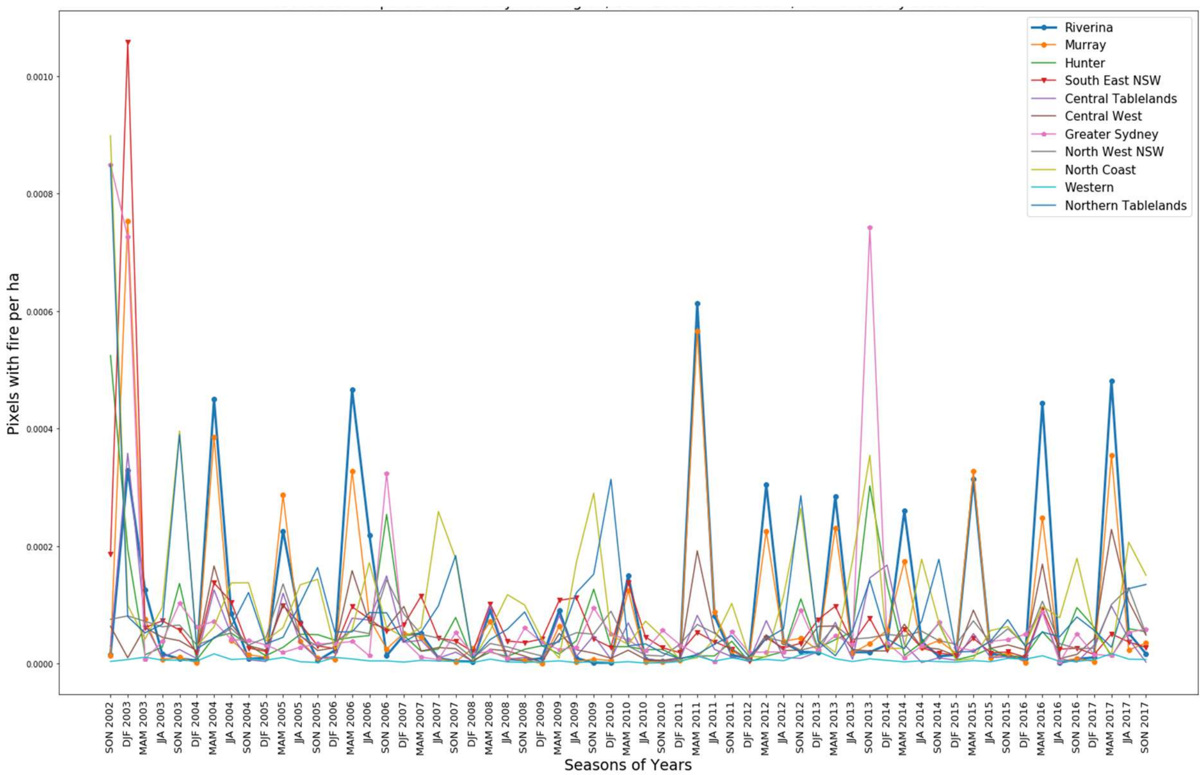


**Figure 5.3.** A seasonal time-series of the relative density of recoded pixels with fire, LLS regions NSW, SON 2002-SON 2017.

Seasonal fire density values, presented in Figure 5.3, display the frequency of detections relative to the total area of the LLS region. The low-level magnitudes of detected fire in South East NSW is further evident, however the Murray region is shown to have frequently attained levels comparable to the Riverina. Elevated amplitudes of activity within the North Coast, Northern Tablelands and Hunter regions during SON suggest comparable detections per ha with the Riverina and Murray in select years, yet generally suggest lower levels of fire coverage.

The relatively small region of Greater Sydney recorded a notable peak in SON 2013, though lacks the consistently defined and distinctly isolated seasonal peaks evident in the Riverina and Murray regions. Broader seasonal distributions of fire activity were found to be common to SON and DJF dominated regions, but also in the MAM associated North Western and Western regions, when compared with distinct seasonality of the Riverina and Murray regions.

### 5.3.7 Interactions between the SOI and NSW burning

A seasonal time-series of state total pixels with fire was overlayed with seasonal SOI values, to illustrate direct associations between the two metrics. The prominent high fire pixel count at the onset of the study period was found to be associated with the 2002-3 El Niño event (Figure 5.4). However stronger El Niño events occurred in subsequent years, with the strongest SOI at < -15 (2016). Not all negative SOI values were followed with peaks in fire activity, resulting in a limited relationship between the count of pixels with fire and the SOI across the year and by seasons.

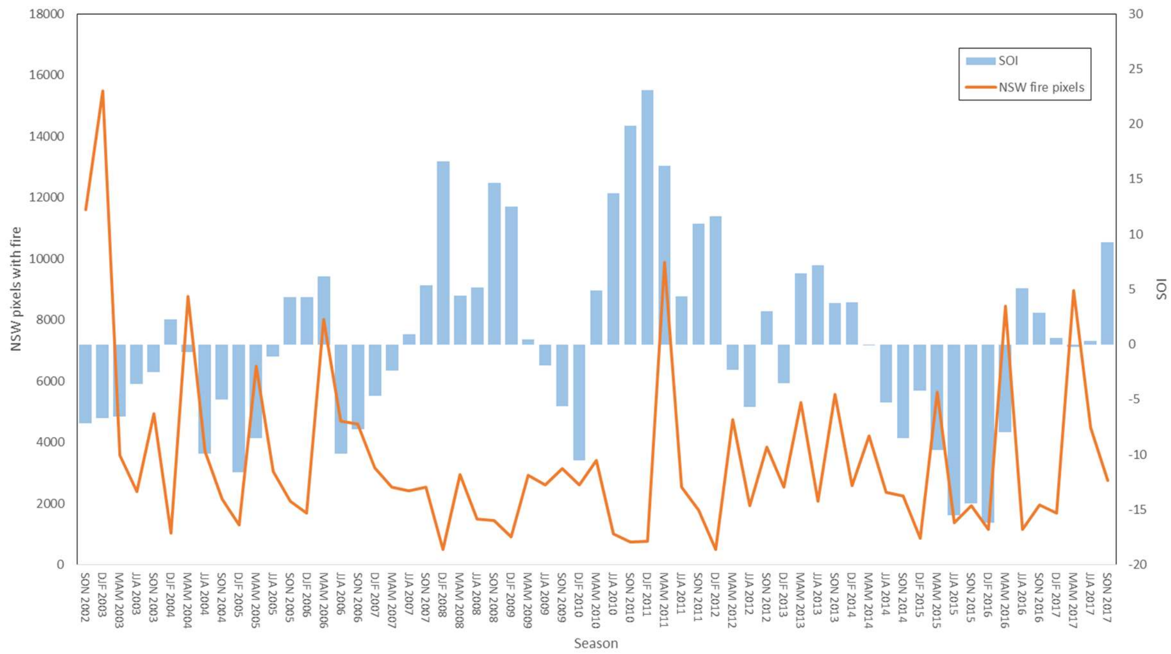


**Figure 5.4.** A seasonal time-series of recoded pixels with fire for the state of NSW, with overlay of seasonal SOI.

Scatterplot comparisons of the SOI and total pixels with fire detected in NSW (Figure 5.5a) revealed a weak, statistically insignificant ($p>0.05$) negative relationship ($y = -69.5x + 3520.2$). Analysis for delayed seasonal fire response to the SOI also resulted in negative relationships, not found to be significant, for -1 SOI seasonal displacement (Figure 5.5b, $y = -24.6x + 3363.7$, $p>0.05$) and -3 SOI seasonal displacement (Figure 5.5d, $y = -1.4x + 3144.9$, $p>0.05$). The -2 SOI displacement, however, exhibited a weak positive relationship (Figure 5.5c, $y= 20.5x + 3146.9$, $p>0.05$).

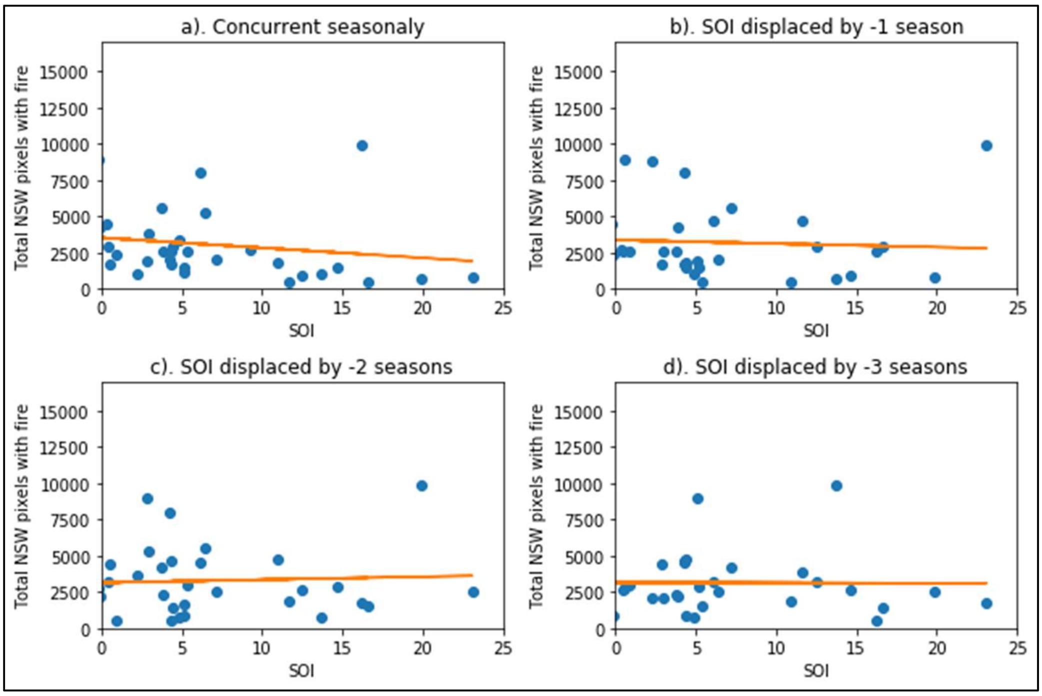


**Figure 5.5.** Scatterplot comparisons of NSW seasonal pixels with fire detection and the SOI seasonal **a)** Both NSW fire detections and the SOI are concurrent, **b)** when the SOI has been displaced by one season, **c)** the SOI is displaced by two seasons, **d)** the SOI has been displaced by three seasons.

A re-plot of concurrent seasonality, with fire seasons distinguished, revealed MAM fire activity to be divergent from other seasons, displaying a positive relationship with the SOI (Figure 5.6a). A similar pattern was also evident in the -2 season SOI displacement, though both MAM and JJA were shown to be counteractive to the negative relationships between the SOI and SON and DJF counts of pixels with fire (Figure 5.7).

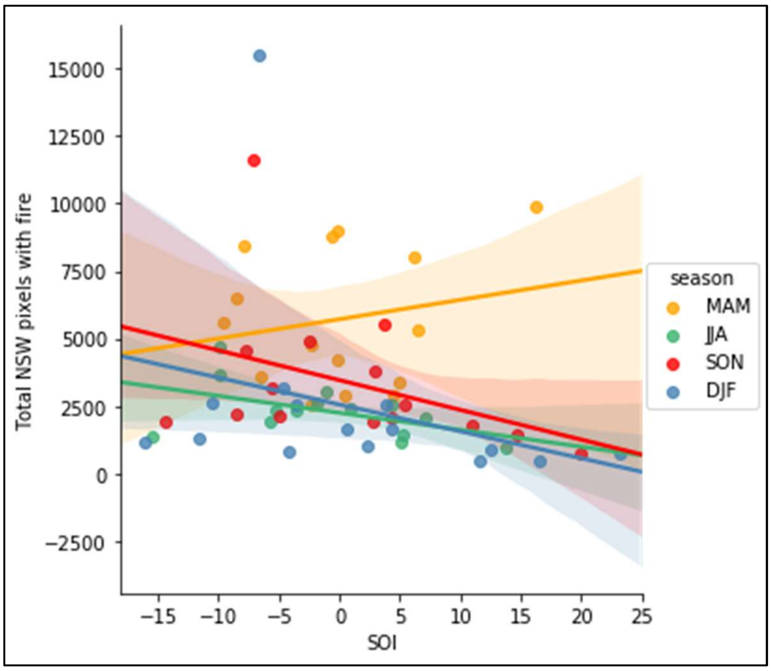


**Figure 5.6.** A scatterplot comparison of concurrent seasonal SOI and total detections of pixels with fire in NSW, distinguished in colour by fire season.

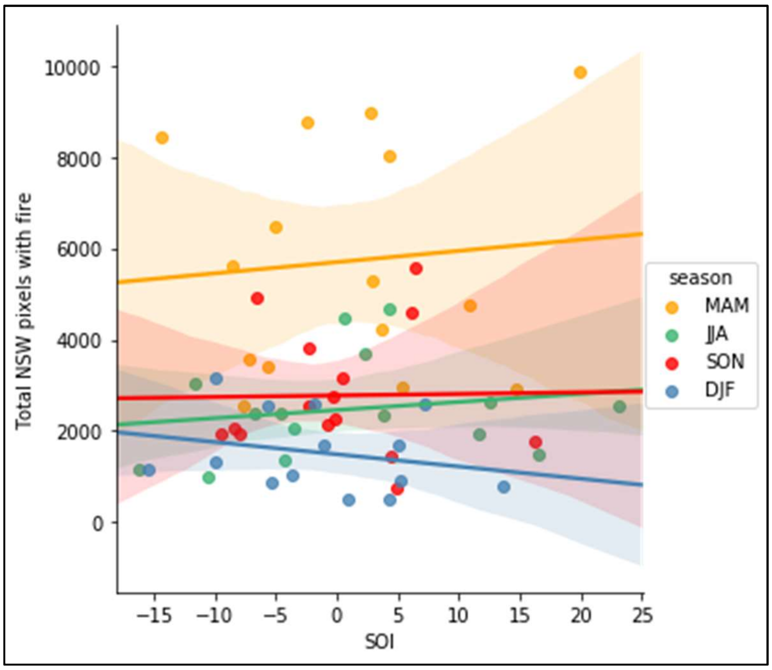


**Figure 5.7.** A scatterplot comparison of seasonal SOI and total detections of pixels with fire in NSW where the SOI has been displaced by -2 seasons, distinguished in colour by fire season.

## 5.4 Discussion

The regional variations of fire frequency and magnitude recorded within NSW may be broadly summarised by four spatially distinct profiles of coarse seasonality. The west is characterised by low amplitude, relatively a-seasonal fire activity; Central regions were indicative of variable, yet highly seasonal recurrent fire activity during MAM; while Coastal and near-coastal regions exhibited a distinct SON seasonality, resulting primarily from infrequent yet high magnitude events. An exception however, occurred within the south east NSW LLS region. Similar to other coastal regions it displayed influence from a conspicuous event of magnitude during the onset of the study period, however the highest magnitudes occurred during the preceding season.

Subsequent years displayed greater MAM seasonality, more aligned with activity observed in central regions. To understand the underlying factors behind this contrasted and somewhat mixed seasonality we must first investigate the most prominent feature observed within each time series in this chapter, the Southeast Australian Bushfires of 2002-2003.

The 2002-2003 bushfire season affected substantial areas of the state, burning of vast tracts of national parkland, forestry and grazing lands, featuring heavily both in the northern and southern coastal and near-coastal regions of the state. Taylor & Webb (2005) describe the initial outbreak and progression of the event, noting the spread from north-eastern NSW during SON, to the southeast of the state in DJF.

This corresponds with findings of heightened detections on the North Coast and Northern Tablelands in SON 2002, followed by South East NSW, Murray and Riverina LLS regions during DJF. Seasonal advancement with latitude by wildfire is commonly experienced in coastal NSW (Taylor and Webb, 2005). A product of the advent of hot, dry westerly winds as well as climatic differences in the seasonal distribution of rainfall (Taylor & Webb, 2005).

North-eastern NSW is characterised by higher summer rainfall and a relatively dry winter (abs.gov.au, 2012). The resulting conditions of low moisture content in soils and vegetation, along with higher temperatures and evaporation rates, assist the curing of fuels and the preconditioning of fire during SON. This is contrasted in the south of the state, where winter dominated rainfall is associated with the passage of cold-fronts. In spite of these climatic distinctions, the South East NSW, Riverina and Murray LLS regions were each affected by the 2002-3 bushfire season in DJF.

Wildfire activity in the warmer months is common to south-eastern Australia as a whole, not only due to curing of fine fuels but also due increased incidences of fire weather and dry lightning ignitions (Bradstock et al., 2014, Verdon et al., 2004). This may be further exacerbated by rainfall deficiencies in preceding months, in addition to above average temperatures, resulting in increased curing of heavy fuels, adding substantially to the available fuel load (Bradstock, 2010).

Seasonal deficiencies of rainfall ensued for much of eastern Australia between 2001 and 2009, during the height of the "Millennium Drought" (van Dijk et al., 2013). Van Dijk et al (2013) found two thirds of the east Australian rainfall deficit within the period to have been explained by the prevailing conditions of the El Niño phase of ENSO.

Despite well-established associations between the ENSO and the occurrence of rainfall (Risbey et al., 2009), fire weather (Verdon et al., 2004) and wildfire (Mariani et al., 2016) within the east of the state, this study found little evidence of a clear association between the SOI and total fire activity recorded within the total area of NSW. Explanations for this finding may include conflicting seasonal influences to rainfall and fire weather from ENSO in different regions of the state (e.g. Verdon et al., 2004). Strong positive correlations between the SOI and rainfall were noted by Mariani et al, (2016) in south eastern Australia during JJA and SON, with weak negative correlations in DJF and MAM. This association was effectively reversed in the north east, which instead correlated positively in DJF and either neutrally or negatively correlated in JJA and SON.

When directly comparing the SOI to recorded fire isolated to the temperate forests of south east Australia, Mariani et al, (2016) found the frequency of unplanned fire to be negatively related to the full seasonal cycle, up to and including a fire season. Results on lagged seasonal influence of the SOI on a state level, within the current study, found weak, statistically insignificant (p value > 0.05) negative associations between the SOI and detected fire in three out of four iterative seasons. The exception, also insignificant, found a positive association between the SOI and fire detections three seasons removed. This was found to be as a result of instances of high magnitude fire detections recorded in MAM following positive SOI values during SON, with a similar yet smaller-scale signal linking higher detections in JJA, following positive values in DJF.

Smith et al (2007) identified a strong MAM seasonal component to winter cropping when comparing fire detection, burnt area and farm management surveys within southwest WA in 2005. Similar patterns of fire detection were observed during MAM within other cropped regions of Australia, including NSW, to which the authors suggest may result from related activities. Current findings of annually recurrent and high magnitude MAM activity within regions consistent with the East Australian Wheat-Sheep Belt, particularly within the Riverina, are supportive of this assertion. Furthermore, it follows that the contribution of cropping associated fire during MAM is adverse, or at least inconsistent, with the negative relationship established between the SOI and wildfire occurrence in temperate forests.

It is therefore likely that the relationship between the SOI and fire occurrence on a state level is confounded by the mixed signals of managed and unmanaged fire activity, each exhibiting independent degrees of interaction with the climatic effects. Mariani et al, (2016) observed fire occurrence in Southeast Australia to be principally linked to ignitions.

Furthermore, Bradstock (2010) and Russel-Smith et al (2007) found the majority of ignitions within Australia to be linked to human intervention.

Bushfire hazard reduction by low-intensity preventative burning is also commonly practiced during MAM in southern NSW. The timing in MAM is favoured due to the reduced likelihood of re-ignition in JJA (RFS, 2014). Controlled burning is likely to account for a considerable amount of MAM activity in the densely forested coastal and near-coastal regions of NSW, where wildfire risks are most apparent. This suggests a degree of cohesion in MAM seasonality between separate applications of managed fire in both cropping regions and forested land uses, the timing coincident with lower risks of wildfire and indicating a clear a land management factor in fire seasonality, governed by land use.

## 5.5 Summary

The distribution and frequency of fire was analysed according to LLS regions of NSW, identifying distinct profiles of fire activity according to seasonal rainfall distribution and influence of managed fire use during periods of minimal fire risk.

The most prominent feature observed in NSW during the study period was the 2002-2003 Bushfires. The results showed heightened detections in LLSs affected by the bushfires, confirming conditions of low moisture content in soils and vegetation, along with higher temperatures and evaporation rates, assist the curing of fuels and the preconditioning of fire.

A clear majority of annually recurrent fire activity was found to occur in MAM, particularly in regions associated to the east Australian Wheat-Sheep Belt and to the Riverina LLS.

There was little evidence to suggest a direct relationship between SOI and state-level fire occurrence. Any interactions therein are confounded by counteracting influences and managed activities that relate to disparate land uses.

# Chapter 6: Land Use Distributions and Fire Frequency in NSW

## 6.1 Introduction

The previous chapter broadly explored the distribution, and frequency of fire between the LLS regions of NSW. It identified profiles of fire activity driven by seasonal rainfall distribution, though detected influence from managed fire use occurring during seasons of minimal wildfire risk. The majority of annually recurrent fire activity within the state was found to occur between March and May and spatially associate within regions aligned to the east Australian Wheat-Sheep Belt, particularly the Riverina region. Comparisons between the SOI and state-level fire occurrence found little evidence of a direct relationship. It was argued that the interactions of climate and fire on a state level were obscured by the counteracting influences and managed activities relating to disparate land uses.

The current chapter measures the influence of key land uses on the frequency of fire within rural NSW, in order to establish whether they explain the spatial variation in fire activity. It identifies and characterises variances in fire seasonality between land uses and in juxtaposition with land use composition within LLS regions. Threats of post fire erosion are discussed in light of primary land use within high risk regions, before the influence of land use change within the study period.

## 6.2 Chapter Aims

The aims developed to address the aims of this chapter are:

1. Which rural NSW land uses display the highest frequencies of detected fire?
2. What is the seasonality of the key land uses?
3. What are the dominant land uses in each LLS?
4. How does land use differ between LLS regions?

5. Does land use change in space and time?

## 6.3 Results

### 6.3.1 Fire Occurrence and fire frequency rankings

Calculation and ranking of mean annual detections by land use type was conducted to identify key land uses associated with the highest frequencies of pixels with fire. Of the top five land uses, Dryland Cropping recorded the highest value of 3,415.53. The second highest ranking was found to be Grazing Native Vegetation, which recorded an annual mean of 2,909.47, followed by Nature Conservation, Other Minimum Use and Production Native Forestry, amounting to 1,919.20, 1,331.60 and 1,069.47 respectively.

Mean annual detections were normalised by the total area of each land use to provide fire frequency values. Of the five selected land use types, Production Native Forestry recorded the highest mean annual density value of $4.56 \times 10^{-4}$/ha, followed by Dryland Cropping ($3.05 \times 10^{-4}$/ha), Other Minimum Use ($2.74 \times 10^{-4}$/ha), Nature Conservation ($2.57 \times 10^{-4}$/ha) and Grazing Native Vegetation ($6.8 \times 10^{-5}$/ha).

The ambiguity of the classification Other Minimum Use was determined to be unsuitable for comparison as it represented an amalgam of varied ancillary uses. Irrigated Cropping was chosen as a substitution due to its prevalence within the influential Riverina region as well as a comparably high mean annual density value of $4.56 \times 10^{-4}$/ha, equal to that of Production Native Forestry.

### 6.3.2 Fire seasonality in NSW

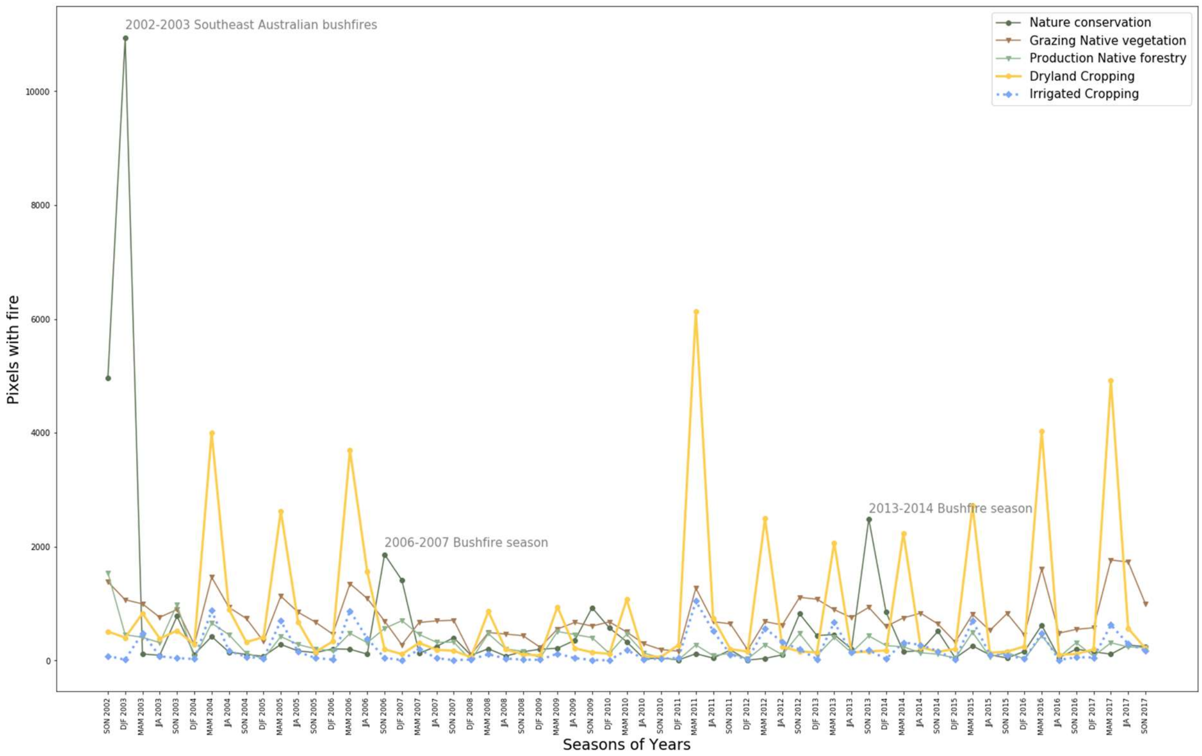


**Figure 6.1.** NSW recorded pixels with fire by select land uses. SON 2002 to SON 2017.

The selected key land uses were compared, in a seasonal time-series of detected pixels with fire, to identify distinguishing temporal profiles and characteristics, (Figure 6.1). With the exception of intermittent large-scale events of magnitude, including the 2002-2003 bushfire season, Nature Conservation was found to display comparatively minimal rates of detection. Prominent events during the 2006-2007 and 2013-2014 bushfire seasons exceed values of Dryland Cropping within the same years, yet are regularly surpassed in other years. Despite prominent examples of associations with both SON and DJF seasons, pronounced activity within these seasons typically displayed low inter-annual frequency. Relatively small-scale elevations were, however, observed to recur during MAM, in seven of the 15 years.

By comparison, Dryland Cropping was shown to feature regular and highly discrete peaks during MAM, frequently exceeding other land uses, with exceptions previously noted. Elevations within JJA were, however, apparent in select years, more frequently between 2004 and 2006, but also in 2011 and 2017. A positive trend in MAM detections is visible between 2013 and 2017.

Similarly, a positive trend between 2013 and 2017 was also apparent during MAM in Grazing Native Vegetation, which also displayed frequent elevations within MAM. However, detections were shown to be more broadly distributed between seasons and smaller in scale. Annual gradients showing decline from MAM to DJF were noted to exist between 2004 and 2006, with subsequent years indicating a more uniform distribution before returning to a more pronounced MAM signal.

Production Native Forestry also indicated elements of regular MAM activity, frequently higher in rate than that of Nature Conservation, occasionally extending into JJA. Similar to Nature Conservation, intermittent large-scale events were indicated in multiple years, primarily during SON, though evident on a much smaller scale.

Irrigated Cropping, despite the relatively small area covered, frequently exhibited elevated detections during MAM, above that seen in Grazing Native Vegetation or Production Native Forestry, but well below the amplitudes of Dryland Cropping. Unsurprisingly, seasonal amplitudes displayed many proportional similarities to that of Dryland Cropping, yet a positive trend between 2013 and 2017 was not apparent.

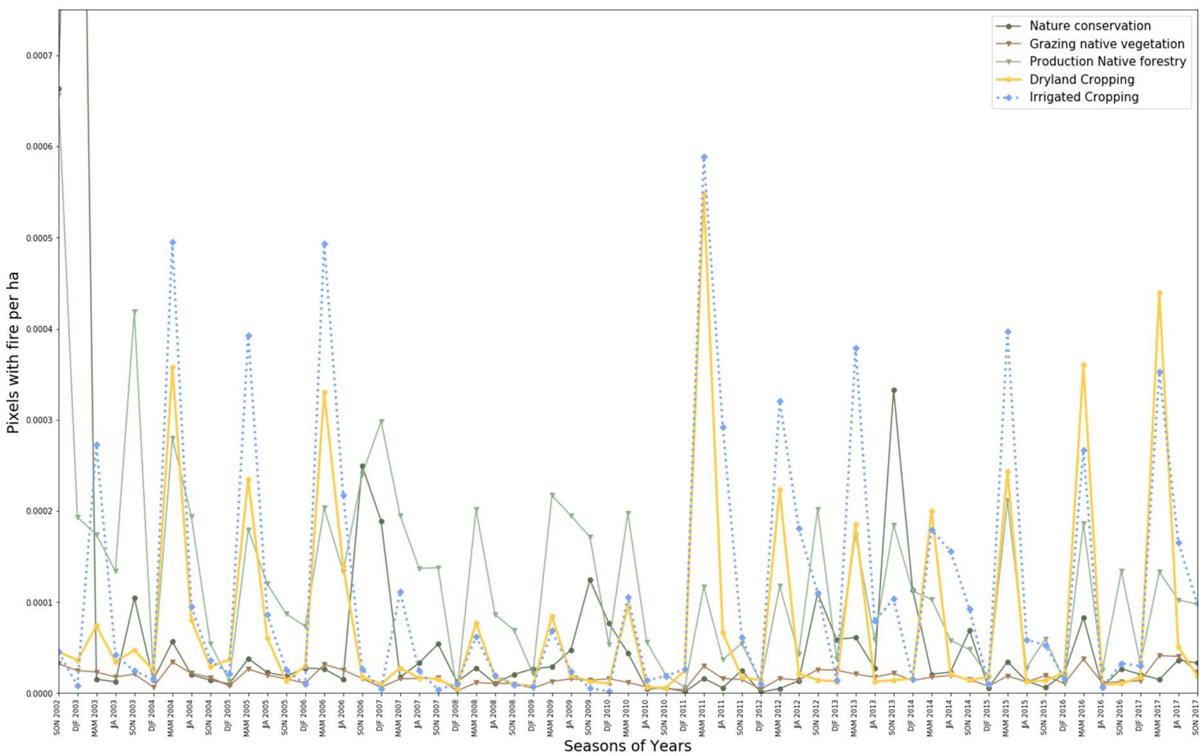


**Figure 6.2**. NSW density of pixels with fire by select land uses. SON 2002 to SON 2017.

A time-series of seasonal density values was conducted to reveal the magnitude and consistency of fire detections, per hectare, in each of the key Land use types, (Figure 6.2). As previously observed, detections within Production Native Forestry were dominated by periodic events, associated with SON and DJF. However, regular elevated density values during MAM were shown to approach levels recorded by Dryland Cropping. In 2003 and between 2006 and 2010, density values of Production Native Forestry demonstrated increased magnitudes concurrent with lower activity observed in Dryland Cropping. Alternatively, in 2011 Dryland Cropping achieved a seasonal density rate of $5.49 \times 10^{-4}$/ha during MAM, while Production Native Forestry attained only $1.17 \times 10^{-4}$/ha, suggesting factors conducive to detected fire in one land use were limiting in the other. Irrigated Cropping, on the other hand frequently attained higher density values than Dryland Cropping in MAM, though seasonality was shown to be less discrete, with comparatively higher elevations regularly observed during JJA, extending to SON between 2011 and 2017.

Seasonal irregularity within Nature Conservation was further highlighted by the contrasts in density between periodic events and intermediate years of low-level detections. The highest seasonal density value of all land uses was attained by Nature Conservation in DJF 2002-2003 at $1.465 \times 10^{-3}$/ha. Otherwise, the majority of seasons fell below $2 \times 10^{-4}$/ha. Exceptions occurred during SON or DJF, in years when similar peaks were observed within Production Native Forestry, inferring a closer association between the land uses. By contrast, the seasonal density values of Grazing Native Vegetation indicated low detections of fire per hectare, throughout all seasons.

**Table 6.1.** Slope and intercept values for seasonal (x) and total pixels with fire, NSW, SON 2002- SON 2017. Ranked in order of maximum seasonal detection of pixels with fire (MaxSPD)

| Land Use | ALUM7 | MaxSPD | SON | DJF | MAM | JJA |
|---|---|---|---|---|---|---|
| Nature Conservation | 110 | 10,943 | 1.36x+ 1191.21 | 1.00x+ 980.18*** | -3.07x+ 2751.54 | -0.83x+ 697.73 |
| Dryland Cropping | 330 | 6,137 | 3.07x+ 2842.82 | 10.06x+ 1271.80* | 1.15x+ 432.82*** | 3.40x+ 1982.20** |
| Grazing Native veg | 210 | 1,765 | 2.56x+ 1105.04** | 1.42x+ 2274.41 | 1.76x+ 1172.01*** | 2.31x+ 1168.35** |
| Irr. Cropping | 430 | 1,043 | 4.03x+ 475.70* | 22.10x+ 285.97** | 1.48x+ 25.53*** | 2.64x+ 353.28*** |
| Prod Native Forestry | 220 | 982 | 1.46x+ 639.32*** | 1.67x+ 855.77** | 1.56x+ 435.19 | 2.36x+ 571.86* |
| Other min use | 130 | 845 | 2.19x+ 253.90*** | 1.31x+ 951.66 | 0.14x+ 1337.86 | 1.83x+ 798.39 |
| Grazing Modified | 320 | 601 | 2.93x+ 389.91* | 1.54x+ 679.74 | 1.62x+ 253.74*** | 2.39x+ 345.41*** |
| Manufacturing & Ind. | 530 | 149 | 3.69x+ 26.56*** | 3.80x+ 80.79*** | 2.61x+ 94.52*** | 3.46x+ 11.53*** |
| Plantation Forestry | 310 | 129 | 5.48x+ 22.70** | 1.84x+ 89.11 | 1.84x+ 22.58*** | 2.32x+ 43.09*** |
| Managed reserve | 120 | 65 | 1.08x+ 17.78*** | 0.40x+ 24.42 | 1.22x+ 9.42* | 1.37x+ 21.65 |
| Services | 550 | 114 | 1.32x+ 39.18* | 1.14x+ 47.23*** | 2.22x+ 57.11 | 3.88x+ 43.97* |
| Residential Farm Inf. | 540 | 97 | 1.32x+ 85.28 | 1.16x+ 100.96* | 1.02x+ 65.23* | 2.02x+ 68.76** |
| Irr. Perennial Hort. | 440 | 25 | 0.94x+ 24.74 | 1.29x+ 28.22 | 0.94x+ 13.18*** | 1.25x+ 20.18*** |
| Perennial Horticulture | 340 | 19 | 0.84x+ 12.80 | 0.36x+ 15.28 | 1.15x+ 6.75*** | 2.06x+ 8.51** |
| Irr. Grazing Modified | 420 | 19 | 1.53x+ 12.75 | 1.29x+ 14.26 | 1.17x+ 3.39*** | 2.31x+ 8.74** |
| Intensive Animal Prod. | 520 | 10 | 2.14x+ 2.92** | 0.81x+ 4.58 | 0.97x+ 2.28*** | 0.32x+ 4.88 |
| Irr. Plantation Forest | 410 | 7 | 1.96x+ 2.43 | 3.92x+ 3.08 | 1.46x+ 0.30*** | 2.28x+ 2.23** |
| Irr. Seasonal Hort. | 450 | 6 | 0.54x+ 2.79 | 0.00x+ 3.00 | 0.93x+ 1.33*** | 0.94x+ 2.44 |
| Intensive Hort. | 510 | 4 | 0.89x+ 0.64 | 0.78x+ 0.74** | 0.00x+ 1.00 | 1.73x+ 0.77 |
| Seasonal Horticulture | 350 | 3 | 0.98x+ 0.41** | - | 0.70x+ 0.75 | 1.81x+ 0.69* |
| Transition LU | 360 | 3 | 1.38x+ 1.25** | 0.11x+ 1.79 | 0.29x+ 1.68 | 1.15x+ 0.81*** |

Seasonal slope values of land use with a MaxSPD value < 100 are considered less reliable indicators of seasonality

Slope and intercept equations were calculated using linear regression to quantify seasonal associations between land use types, (Table 6.1). Each land use season was calculated from the period DJF 2002-2003 and SON 2017, (N=15), with outliers retained, including large scale events during 2003, 2006 and 2013. The significance of results are denoted by asterisks (*=$\alpha$<0.05, **= $\alpha$<0.01, ***=$\alpha$<0.001).

Slope values represent the linear contribution of detections recorded within a particular season in relation to the sum total value within each dryland land use type. Significant slope values approaching a whole value of one indicate a strong seasonal influence. Negative values result from the influence of low seasonal values during outlier years. Inflation of slope values by outlier values was also common to SON and DJF seasons. Land uses were ranked by maximum seasonal fire pixel detections (MaxSPD), with quantities below 100 considered to be less reliable indicators of seasonality and more likely influenced by stochastic events. Coloured cells distinguish fire seasonality between high wildfire risk (red) and low (blue). Fires occurring during SON and DJF coincide with seasonal wildfire activity and greater restrictions to managed burning in NSW, while fires in MAM and JJA are counter-seasonal to high wildfire risk, occurring in a period when managed burning is facilitated by a reduction to fire restrictions.

Nature Conservation, Production Native Forestry, Managed Reserve and Services each demonstrated strong associations with the high wildfire risk seasons of SON and DJF, while land uses indicative of greater modification, such as those associated with cropping and grazing, presented a clear bias toward MAM and JJA.

Scatterplots of land uses displaying the five highest MaxSPD values reveal the influence of individual seasons on slope and intercept values (Figure 6.3). Native Conservation shows influence from outlier values associated with both SON and DJF, though is dominated by a single event in DJF 2002-2003 resulting in a slope value approaching 1x for that season (Figure 6.3a). By comparison, detections in Grazing Native Vegetation were almost completely dispersed within a region of weak seasonality (>2x), exhibiting low seasonal definition, though MAM values are shown to be most influential and DJF values least influential, particularly during 2017 (Figure 6.3b).

Production Native Forestry, similarly to Native Conservation, demonstrated disproportionate influence from a small quantity of points associated with SON and DJF, (Figure 6.3c), however six points of MAM within the boundary of strong seasonality (<2x) suggest an underlying pattern of influence associated with the season.  Dryland Cropping, on the other hand, exhibited strong, regular and distinct MAM seasonality (Figure 6.3d), as did Irrigated Cropping, albeit with higher rates of dispersion within the season.

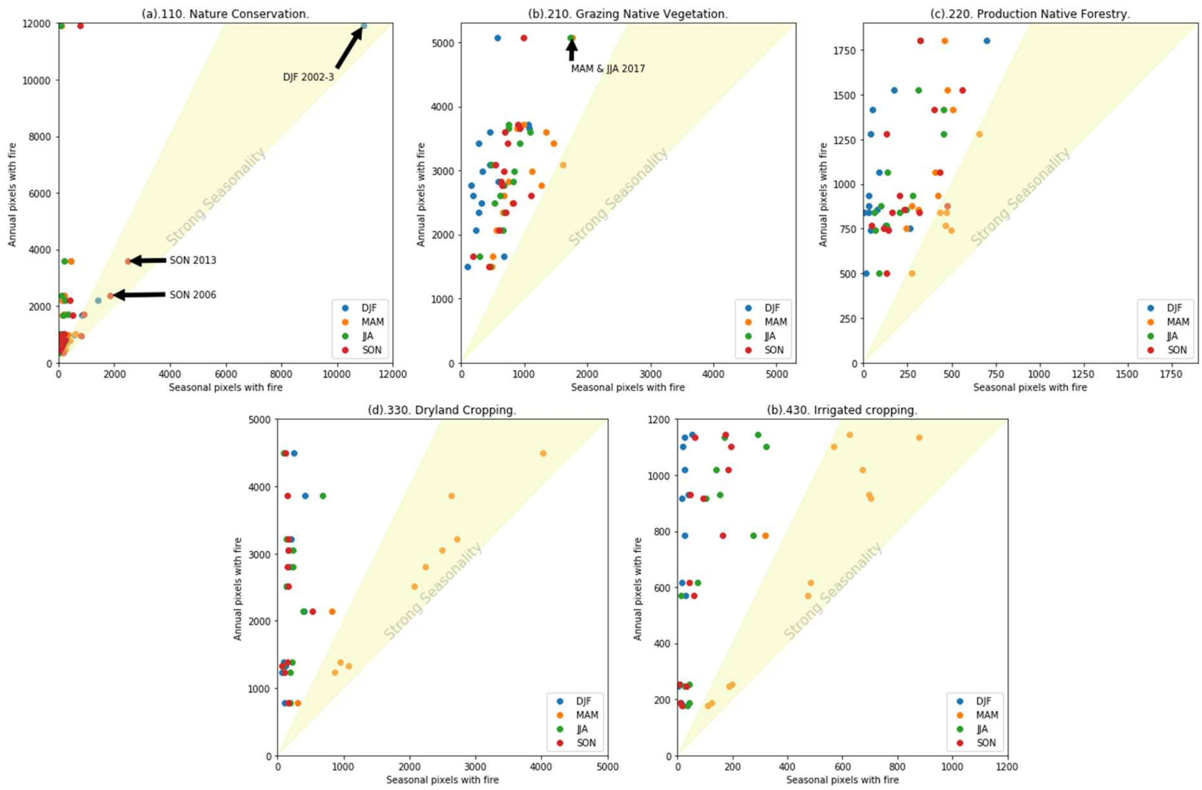


**Figure 6.3.** Scatterplots comparing seasonal to annual fire detections for land uses displaying the five highest MaxSPD in Table 3.1, consisting of - **a)** Nature Conservation, **b)** Grazing Native Vegetation, **c)** Production Native Forestry, **d)** Dryland Cropping, and **e)** Irrigated Cropping. The coloured fill area represents strong seasonality, indicating a slope between y=1x and y=2x with a zero intercept.

### 6.3.3 Distribution of land use within NSW

Land uses range in assortment and extent within rural NSW, with varying proportions of land use area distributed geographically between LLS regions. Of the five key land uses investigated, the expansive Western LLS, typified by low levels of mean annual fire detection, was found to be dominated by Grazing Native Vegetation, which covers close to 70% of the region's total area (Figure 6.4).

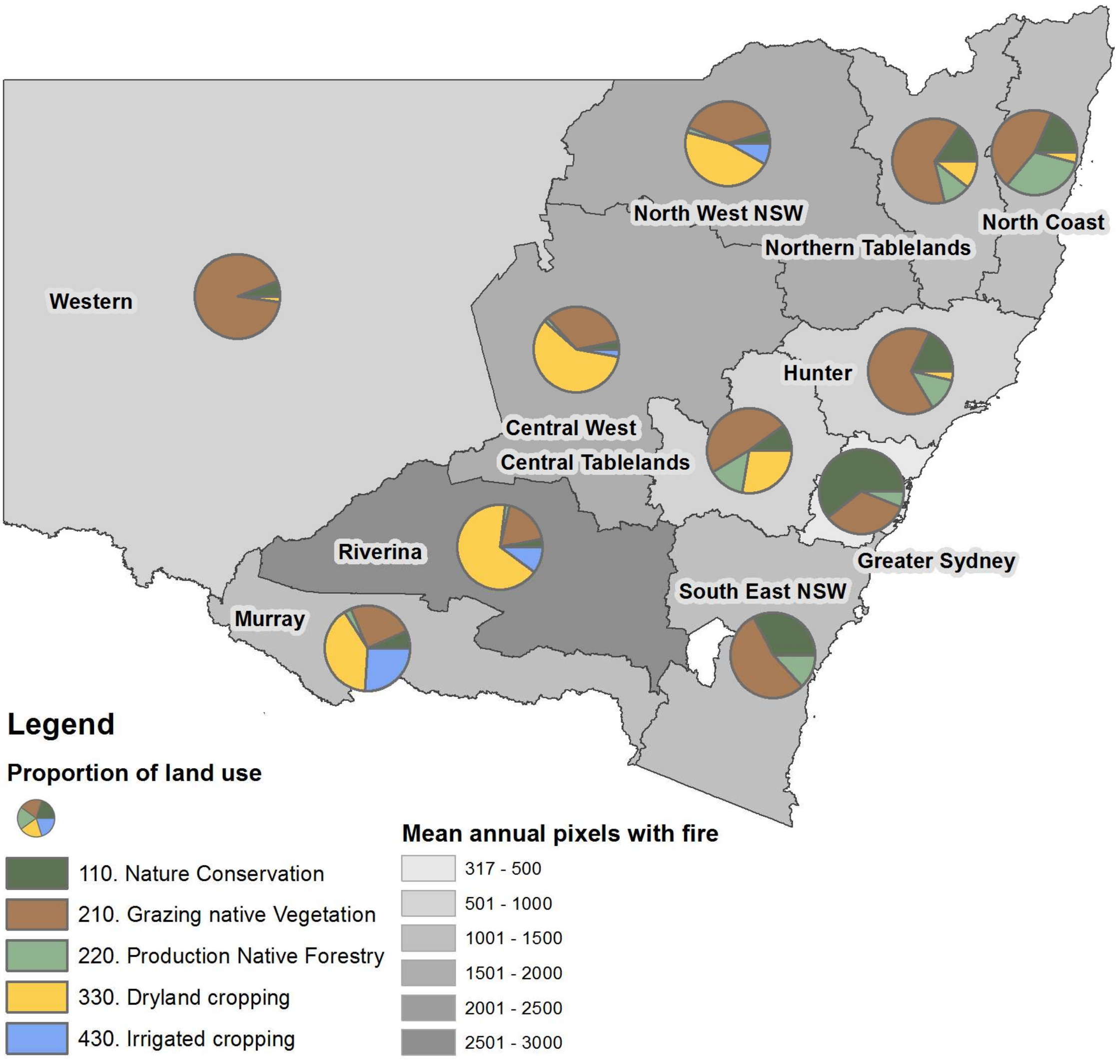


**Figure 6.4.** Proportions of land use for each NSW LLS overlayed on a choropleth of mean annual detections of pixels with fire.

The fire active LLS regions of Riverina, Murray, Central West and North West were each highly representative of cropping land uses, displaying a majority proportion of Dryland Cropping and minimal proportions of forested land uses such as Nature Conservation and Production Native Forestry. Irrigated Cropping was found to be most prominent in the Murray and Riverina regions, which despite displaying varying rates of mean annual fire detection, both exhibited high levels of fire frequency. Area related to Grazing Native Vegetation was also noted to be comparatively smaller than other regions.

Coastal and near-coastal regions were mostly indicative of Grazing Native Vegetation land use, though contained the highest proportions of Nature Conservation and Production Native Forestry. Higher proportions of Production Native Forestry were present in the North Coast LLS, while Greater Sydney and South East NSW each contained greater portions of Nature Conservation. Dryland Cropping was evident within the Central tablelands, Northern Tablelands and North coast LLSs, though highly limited in Greater Sydney and the South East, occupying only 0.13% and 0.35% of the total LLS areas respectively.

A comparison of the extent of cropping land uses between 2007 and 2013 revealed greater densities in most LLS regions due to a 52% increase in the total area of Dryland Cropping within NSW from 7,375,646 ha in 2007 (Figure 6.5a) to 11,188,088 ha in 2013 (Figure 6.5b). Within the same period, Irrigated Cropping, occupying a much smaller area relative to Dryland Cropping, increased a substantial 217%, from 559,845.35 ha in 2007 to 1,772,130.73 ha in 2013. Lower densities of dryland and irrigated cropping were also observed to the eastern and western extents of the Riverina and Murray regions.

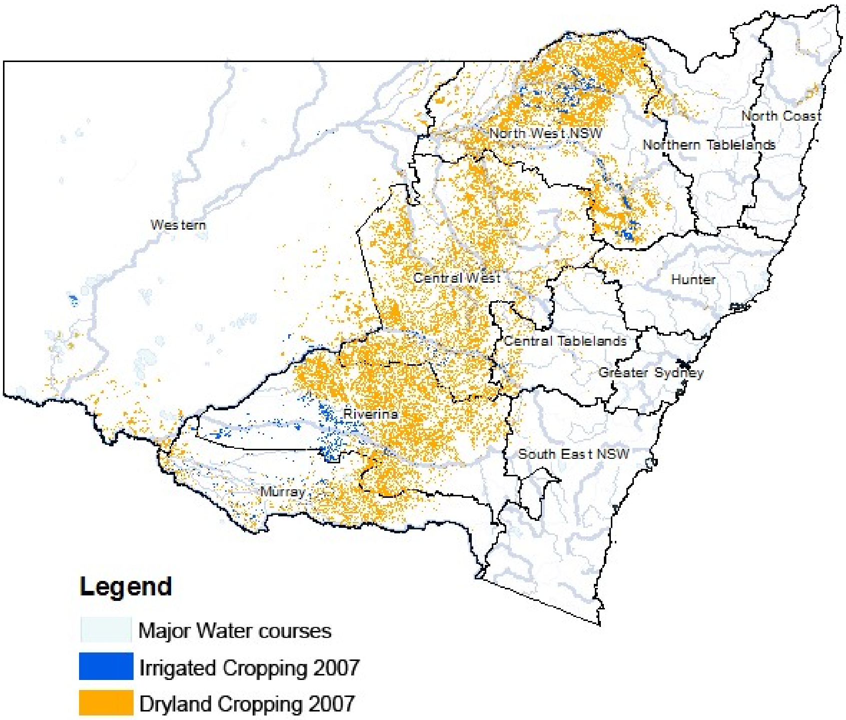


**Figure 6.5a.** Comparison of Irrigated and Dryland Cropping in NSW in 2007.

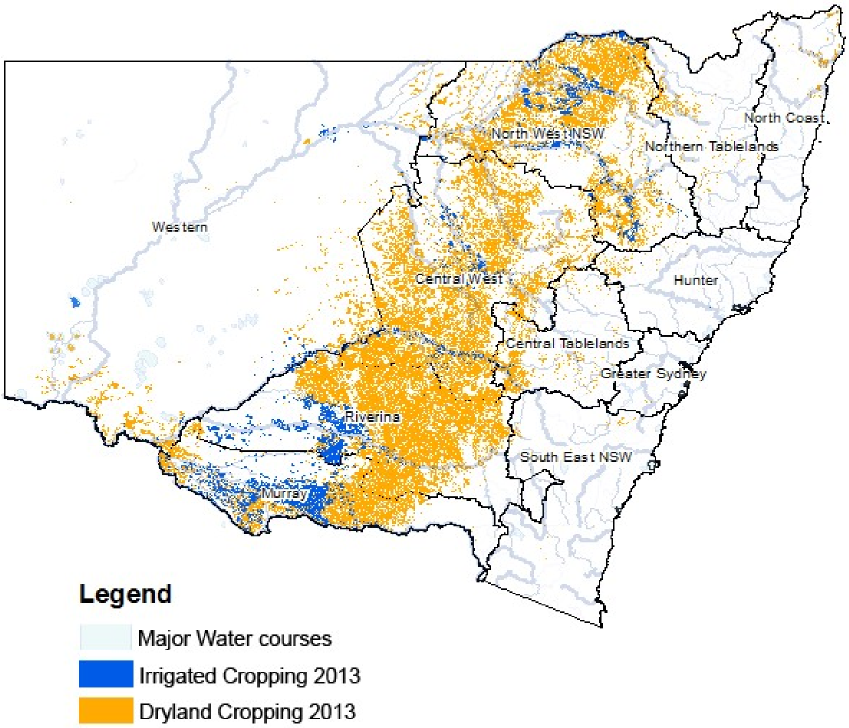


**Figure 6.5b.** Comparison of Irrigated and Dryland Cropping in NSW in 2013.

On a state scale, the Riverina was shown to be the highest contributor to detected fire during MAM, with exceptions between 2007 and 2009 (Figure 6.6). The cropping regions of Central West, Murray and North West follow, with minor influences evident in the western and central tablelands. Forested South East NSW on the other hand, produced the greater proportion of detections between 2007 and 2009.

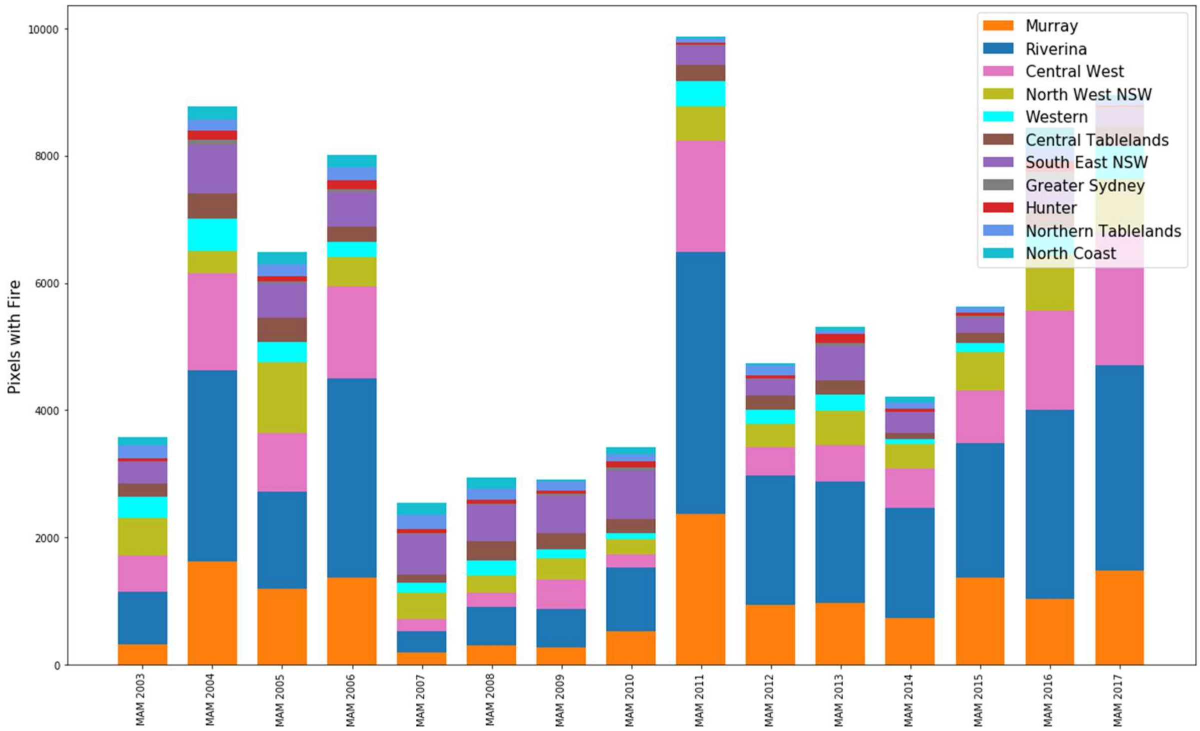


**Figure 6.6.** The contributions of NSW LLS regions to pixels with fire during MAM, 2003-2017

## 6.4 Discussion

Seasonal profiles of fire detection between land uses support the assertion of cropping land uses as major drivers of annual fire activity within rural NSW. Observations of significant and annually recurrent activity related to Dryland Cropping account for the majority of detections during MAM, which has been shown to be the most influential fire season in NSW on an annual basis (Chapters 4 and 5). Detections within MAM are furthermore both seasonally and spatially associated with LLSs consistent with widespread cropping, in particular the Riverina and Murray LLSs, which exhibit both distinct and regular fire seasonality as well as high fire frequencies (as discussed in Chapter 5).

The regularity of this seasonal patterning contrasts heavily with the less frequent, yet potentially severe episodes of wildfire during SON and DJF, most prevalent in Nature Conservation and Production Native Forestry land uses. Both land use types have demonstrated high magnitudes of fire detection in seasons corresponding with significant bushfire events, including the 2002-2003 Southeast bushfires, the 2006-2007 and 2013-2014 bushfire seasons, (indicated in Figure 6.1).

Such a contrast reflects a disparity in seasonality between managed and unmanaged fire, driven by land use and the seasonality wildfire risk. The statutory Bush Fire Danger Period in NSW runs from October to March, though may vary by location (RFS, 2014). Burning within the danger period may be conducted only with the issue of a Fire Permit, though not on days where a total Fire ban has been declared (RFS, 2014). Burning outside of the danger period is more favourable, however, and may be conducted without the requirement of a permit, provided the risks of damage to property are low.

Indications of cool season fire activity were observed in both Production Native Forestry and Nature Conservation, though densities were found to be considerably higher in the former. Interestingly, their occurrence was most common in years when Dryland

Cropping saw reductions, suggesting further evidence of mixed climate responses related to both land management and land use (as discussed in Chapter 5). Detections observed during MAM in both land uses are likely attributable to hazard reduction burning, primarily in the south east of the state. Similar levels observed during SON may likewise result from managed burning in the north east, where controlled burns are conducted before the onset of DJF rains (RFS, 2014).

The combination of high magnitude bushfire activity and counter-seasonal burning subsequently results in Production Native Forestry attaining one of the highest rates of fire frequency analysed. Spatially, however, the land use is poorly represented between LLS regions, as its coverage is comparatively limited compared with other land uses, with the exception of the North Coast LLS, which recorded the second highest fire frequency ranking.

Risks of hillslope erosion are evident within the native forestry and conservation areas of the North Coast LLS resulting from the combination of steep topography and high rainfall erosivity within the region (McKenzie NJ et al., 2017, Yu and Rosewell, 1996). The removal of vegetation and litter cover by fire reduces both rainfall interception and surface roughness leading to increases in soil detachment as well as the volume and velocity of overland flow, which is further exacerbated by post-fire increases in soil water repellency (Shakesby et al., 2007). The seasonality of fire within this region before the onset of convective DJF rainfall suggests heightened susceptibility of water erosion within the immediate post-fire recovery period, indicating both a region and land use of concern.

However, this circumstance is less apparent in southern coastal regions, including South East NSW, which despite displaying lower proportions of Production Native Forestry within the LLS, covers a considerably larger area with more extensive sections of both land uses. Steep slopes are also present within the region, and while there is evidence of MAM burning prior to JJA rainfall, erosivity is considered a reduced threat within the region, despite considerable amounts of observed annual fire detections.

Grazing Native Vegetation accounts for a greater amount of mean annual fire detections than both Nature Conservation and Production Native Forestry state-wide, though presents the lowest fire frequency ranking of the assessed land uses. It is the most extensive land use within NSW; it is also broadly represented in all NSW LLS regions, though is most concentrated within the Western LLS.

The practice of burning grazing land is typically pre-emptive to anticipated rainfall. Pasture is commonly burnt for the purposes of reinvigoration, to provide fresh 'green pick' for animal consumption (Tasker and Bradstock, 2006), or selection of favourable pasture species and the removal of woody vegetation (Hunt et al., 2014). Subsequently, pasture burning is most frequently preformed preceding seasonal breaks to maximise productive growth (Tasker and Bradstock, 2006). While much of NSW is characterised by uniform rainfall, the presence of rain bearing fronts during JJA provides a more reliable and widespread expectation for inland rainfall, especially compared to less predictable events involving localised convection, cut-off lows and tropical interactions (Risby et al., 2009; Bradstock et al., 2013).

Despite increasing aridity and a reduction of wildfire risk (Vermeire et al., 2005) toward the western extent of the state, the Western LLS has shown higher percentages of detected fire during MAM, though indicates a broad seasonal distribution within other seasons (Chapter 5, Table 5.1) and lower fire frequencies. This was reflective of Grazing Native Vegetation throughout the state, though minimum fire activity during JJA contrasted with a state-wide minimum during the fire risk season of DJF. Heightened risks of widespread accelerated wind erosion have been identified within the region's extensive rangelands primarily driven by the impacts of grazing pressure (Leys et al., 2017), yet potential exists for erosion to be intensified by fire use.

Grazing pressure is inherently linked to stocking rates and results in the modification of surface soil stability as well as reductions to vegetation cover from over grazing (Aubault et al., 2015). While litter accumulation is comparatively low within the arid regions (Bradstock, 2010), the spread and intensity of grassland fire is also affected by stocking rates, as grasses may be eaten down before they become fully cured (Cheney et al., 2008). Subsequently, the impacts of fire occurrence in grazing land are dependent on periods of stock exclusion, or pasture 'resting' both before and after burning, as well as amounts of successive rainfall (Hunt et al., 2014, Vermeire et al., 2005).

The spread and intensity of fire on grazing land is also linked to composition of grass species, including the influence from heavier invasive species (Cheney et al., 2008). Not only does fire contribute to the direct removal of vegetation biomass, it may also facilitate further reductions, such as exposing otherwise protected ground-level annual and ephemeral plants to grazing when perennial tussock grasses are burnt (Cheney et al., 2008). Consequently, increasing soil surface exposure and reducing surface roughness.

Regardless, low fire frequency rates observed within Grazing Native Vegetation present a less immediate concern of direct impacts from fire when compared with those attributed to cropping areas. Dryland Cropping attained the third highest fire frequency of the assessed land uses, though covers a considerably greater area of NSW than both Production Native Forestry and Irrigated Cropping. As a consequence, it produces the highest value of mean annual fire detections of all land uses in NSW, primarily during MAM, which coincides with annual burning of winter crop residues, (Smith et al., 2007).

Crop residue or 'stubble' burning is a management practice conducted as an efficient and generally effective solution for the removal of waste biomass, though has further applications, relating to the control of pests, disease and weeds carried over from prior rotations (Smith et al., 2007). Conservation farming practices promote the retention of stubble to reduce soil erosion, conserve nutrients and moisture and improve soil structure and water infiltration (Scott et al., 2010, Smith et al., 2007) To reduce both moisture-loss and the period of soil exposure post-harvest, stubble from winter cropping is often maintained over DJF and burnt prior to the following winter crop during MAM (Scott et al., 2010). This is most evident in the Riverina, which displays the highest proportion of Dryland Cropping of all NSW LLS/LLS regions, while producing the majority of MAM fire activity in NSW. The management of cropping stubble, however, is subject to regional variations.

Similar to the divergent seasonality of hazard reduction burning in forested land uses, Scott et al (2010) found the timing of reported stubble burning in northern NSW to mostly correspond with harvest during DJF, rather than MAM. While the results of LLS fire seasonality pertaining to North West NSW (Chapter 5, Table 5.1) do not conclusively support this finding, they do convey a reduced percentage of MAM detections as well as a higher total count of DJF detections when compared with other cropping regions. Scott et al (2010) also note the reporting of higher rates of stubble retention and incorporation by ploughing within northern NSW due to higher risks of water erosion, related to DJF rainfall erosivity.

Conversely, cropping regions in southern NSW, such as the Riverina and Murray, were determined to exhibit lower risks of water erosion due to reduced rainfall erosivity and gentle sloped topography (Scott et al., 2010). Stubble retention within the region was reported to be the lowest in NSW, attributed to rainfall driven yields producing dense stubble loads (Scott et al., 2010). Stubble management primarily consisted of burning, with low rates of grazing and mulching conveyed. This is reflected by higher reporting of stubble burning within southern NSW (51% of respondents), compared with Central (34%) and northern (11%) NSW (Scott et al., 2010).

The burning of stubble prior to sowing presents a considerable risk of wind erosion between the time of removal in MAM and seedling emergence in JJA, particularly in the Riverina region. The Riverina and Murray regions are however highly representative of Irrigated Cropping, which recorded a land use fire frequency equivalent to that of Production Native Forestry. Both regions also exhibited the highest and second highest fire frequencies recorded in this study, despite containing considerable portions of other land uses. Spatial analysis has revealed dense clustering of the land use associated with areas of irrigation within each LGA.

The Riverina spans a greater area than the Murray LLS, which accounts for the disparity of total annual fire detections between the regions. However, it is unclear whether the high frequencies linked to the Riverina LLS are primarily influenced by Irrigated Cropping or the comparative density of Dryland Cropping within the region. Dryland Cropping displays greater proportions, relative to total area, compared with Central and North Western LLS regions.

Irrigated crops grown within the Riverina LLS include winter cereals and canola, common to Dryland Cropping, as well as rice, cotton and corn. Rice is grown throughout summer, though residual stubble is ordinarily burnt directly after harvest in MAM (NSW EPA, N.D.) concurrent with cereals and canola. The management of rice fungal diseases, prevalent in the Riverina and Murray regions, such as sheath spot and aggregate sheath spot, is dependent on the burning of rice stubbles to reduce carry over of dormant inoculum from prior rotations (Lanoiselet *et al.* 2005).

Subsequently, retention, incorporation and mulching are considered undesirable methods of stubble management, due to the risks of disease transfer. Furthermore, high levels of silica within rice straw limits its practical use as fodder in mixed grazing (Sidhu et al., 2007). The risks of erosion during rice establishment are reduced on account of water management of flooded paddocks, however the period of establishment in post-harvest rotations poses greater potential for localised effects. Such risks are not constant in time, however, as changes to land use may occur in response to numerous drivers such as water availability and economic pressures.

The increases in area for both Dryland and Irrigated Cropping land uses across NSW are consistent with expectations of growth following an extended period of drought. However, there is evidence in literature that suggests Dryland Cropping area continued to extend throughout the years of the Millennium Drought. As irrigation in NSW had seen decline during 2007 on account of reduced water usage, favourable commodity prices for cereals in 2007 fuelled expansion in Dryland Cropping (Kirkby and Fattore, 2006). Van Dijk et al (2013) observed a rise in wheat production volume throughout the Murray Darling Basin during the drought, despite a 12% decline in yield per unit area. This was attributed primarily to increases in Dryland Cropping area working in concert with ongoing water and conversion efficiencies employed to mitigate the effects of rainfall deficiencies.

Declines in wheat yields, and subsequent reductions to wheat stubble loads during the later stages of the Millennium Drought (2007-2010) consequently resulted in lower rates of stubble burning within this period, (as evidenced in Chapter 5, Figure 5.2). However, measurements of cropping land use change between 2007 and 2013 remains problematic. While the 2013 land use dataset displays consistent levels of currency, analysis of the 2007 land use dataset reveals source acquisition dates to be highly variable, extending as far back as 1996. It is determined to be on the whole less contemporaneous than the 2013 dataset and subsequently less representative of the year.

## 6.5 Summary

Of the key land uses selected, both Production Native Forestry and Irrigated Cropping attained the highest fire frequencies. The seasonality of key land uses was shown to vary according with wildfire risk. Irrigated cropping displayed a consistent MAM seasonality, indicating a higher degree of land management influence. Production Native Forestry, on the other hand, displayed greater adherence to wildfire risk seasonality, despite some patterns indicative of managed burning.

Dryland Cropping and Grazing Native Vegetation also exhibited MAM seasonality, though produced lower fire frequencies. Dryland Cropping, however, accounted for a greater contribution to total fire occurrence, when compared to Irrigated Cropping, due to its more expansive coverage. It also displayed the strongest MAM signal of all land uses and was broadly represented in both the Australian Wheat-Sheep Belt and in the Riverina.

Increases in total fire detections post 2010 coincided with cropping area expansion in NSW. Both Dryland and Irrigated Cropping experienced growth between 2007 and 2013, though increases were most extensive in Dryland Cropping. The source of increased burning in the Riverina remains uncertain however, and will be investigated in the following chapter.

# Chapter 7: Frequency of Fire Within the Riverina

## 7.1 Introduction

The previous chapters have identified Riverina LLS region as the most fire prone region in NSW. A strong associated pattern of fire seasonality within the region during MAM was found to be linked with managed fire activities related to Dryland Cropping, observed to be the primary land use within the region. However, comparatively higher fire frequencies found within the region distinguish it from others with similar ratios of Dryland Cropping.

The current chapter investigates the relationship between fire frequency and land use within the Riverina LLS region. It identifies Local Government Areas (LGAs) which display the highest fire frequencies and applies the associations between land use and fire frequency, occurrence, seasonality and density, as detailed in the previous chapter, in order to show the consistency of patterning between scales. It furthermore explores whether land use changes within the study period have contributed increased fire detections post 2010.

## 7.2 Research questions

1. Which LGAs in the Riverina display the five highest fire frequencies?
2. What is the seasonality of burning within the identified LGAs?
3. Which land uses are associated with the identified LGAs?

## 7.3 Results

### 7.3.1 Riverina LGA total detected fire and frequency rankings

Of the 15 LGAs within the Riverina LLS region, the five highest ranking areas of total mean annual detections consisted of Snowy Valleys, which recorded the highest rate of 563.07, followed by Murrumbidgee, Hilltops, Lockhart, and Wagga Wagga, 283.27, 243.00, 225.60 and 215.60 respectively (Appendix 2 Table 3). Fire frequencies, calculated from annual mean density values, on the other hand, were dominated by Griffith, Leeton, Junee, Lockhart and Coolamon, each recording $9.11 \times 10^{-4}$/ha, $7.97 \times 10^{-4}$/ha, $7.90 \times 10^{-4}$/ha, $7.79 \times 10^{-4}$/ha and $6.93 \times 10^{-4}$/ha, per-annum respectively (Appendix 2, Table 3).

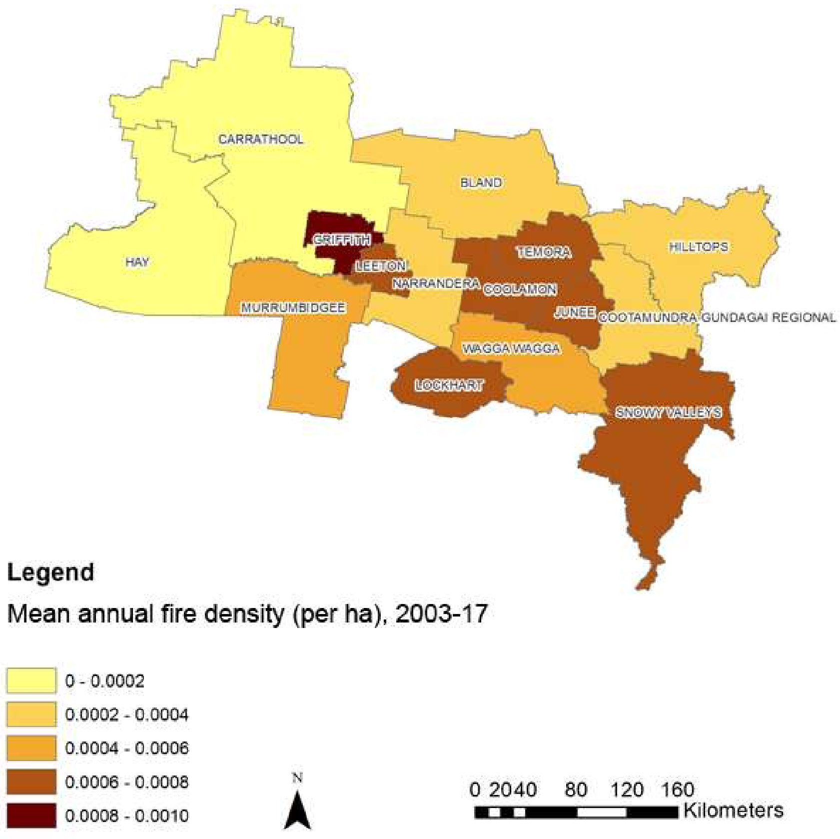


**Figure 7.1.** A Choropleth map detailing the distribution of fire mean annual densities throughout Riverina LGAs. Fire frequencies were calculated per ha for the 2003-17 period.

### 7.3.2 Fire seasonality

A time-series of seasonal detections revealed a contrast in fire seasonality between Snowy Valleys and other Riverina LGAs (Figure 7.2). Snowy Valleys was shown to have been disproportionately influenced by high magnitude activity in DJF 2002-2003, coinciding with the impacts of the Southeast Australian Bushfires, as detailed in previous chapters. Other incidences of high-level DJF were apparent in 2007 and 2014, however, regular lower-level activity was also apparent during MAM. In contrast, Murrumbidgee, displayed maximum values during MAM in all but one year, yet also exhibited high values in JJA and SON, most prominently in the years subsequent to 2011. A similar pattern was observed, at lower magnitudes, within Griffith, Leeton and Carrathool.

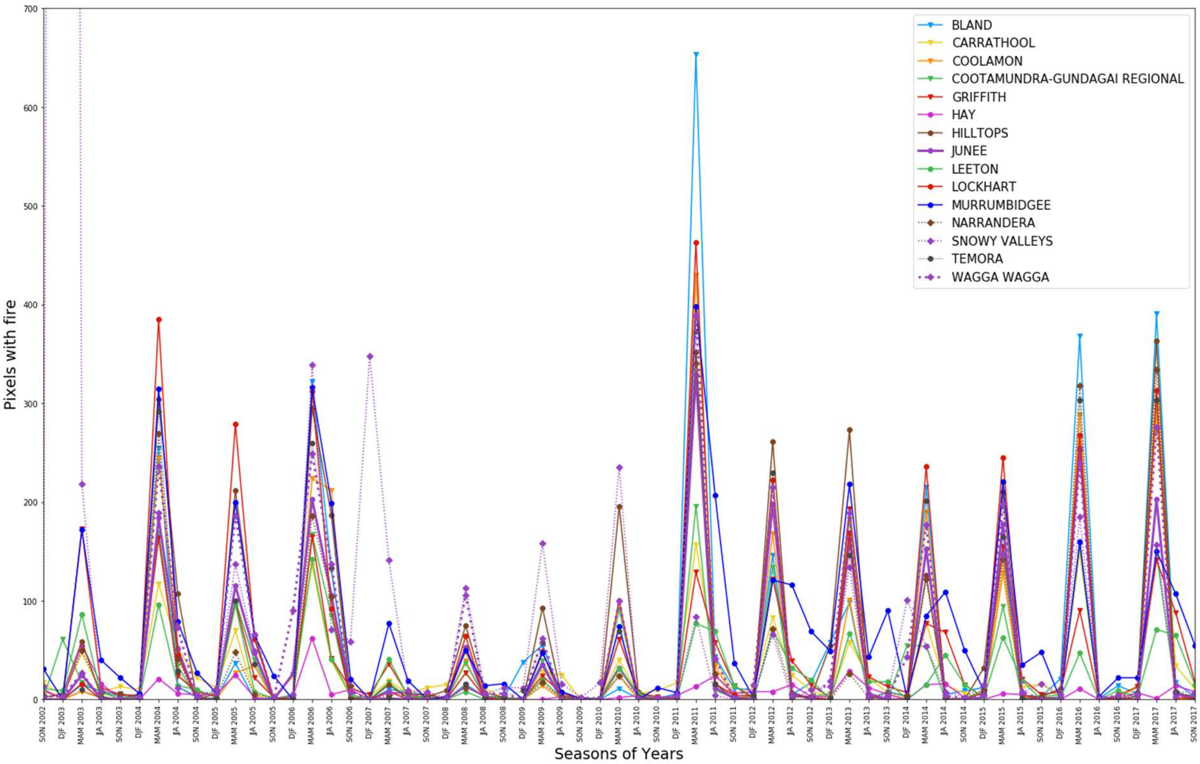


**Figure 7.2.** Time-series of seasonal detections of pixels with fire for each Riverina LGA. SON 2002 to SON 2017. Though obscured, Snowy Valleys obtained a maximum value of 5227 in DJF 2002-2003.

Annual MAM activity clearly exhibits strong variability (Figure 7.3). Clear low fire years include 2005, 2007, 2008, 2009 and 2010 occurring consistently across the region. Peak in activity occurred in 2011 with the Bland LGA recording highest counts in the record. After a slight frequency decrease in 2014, an increasing trend is occurring. Bland and Coolamon once again exhibiting the highest fire detections. Hay and Leeton do not follow the MAM seasonality trends (Figure 7.3).

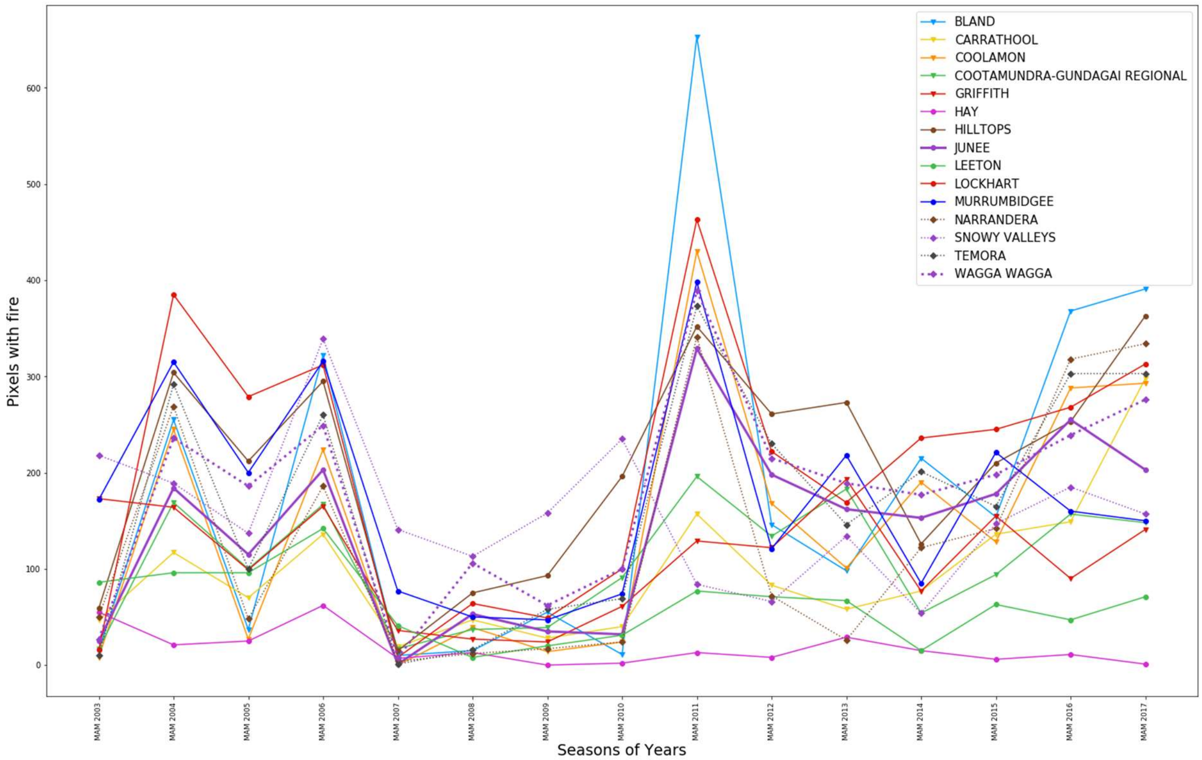


**Figure 7.3.** Annual MAM detections of fire for each Riverina LGA, 2003-2017**.**

A time-series of seasonal fire densities displayed little consistency in LGA positioning between years, with less than a third of maximum values attributed to Griffith (Figure 7.4). Higher densities during MAM, JJA and SON in Griffith and Leeton were found to frequently exceed those of Murrumbidgee. Junee, Lockhart and Coolamon by comparison demonstrated comparatively low magnitudes during JJA and SON, with exceptions noted within the 2004-06 period. Density values for Snowy valleys remained low during MAM and a period of reduced seasonal fire densities was evident for all LGAs between 2007 and 2010.

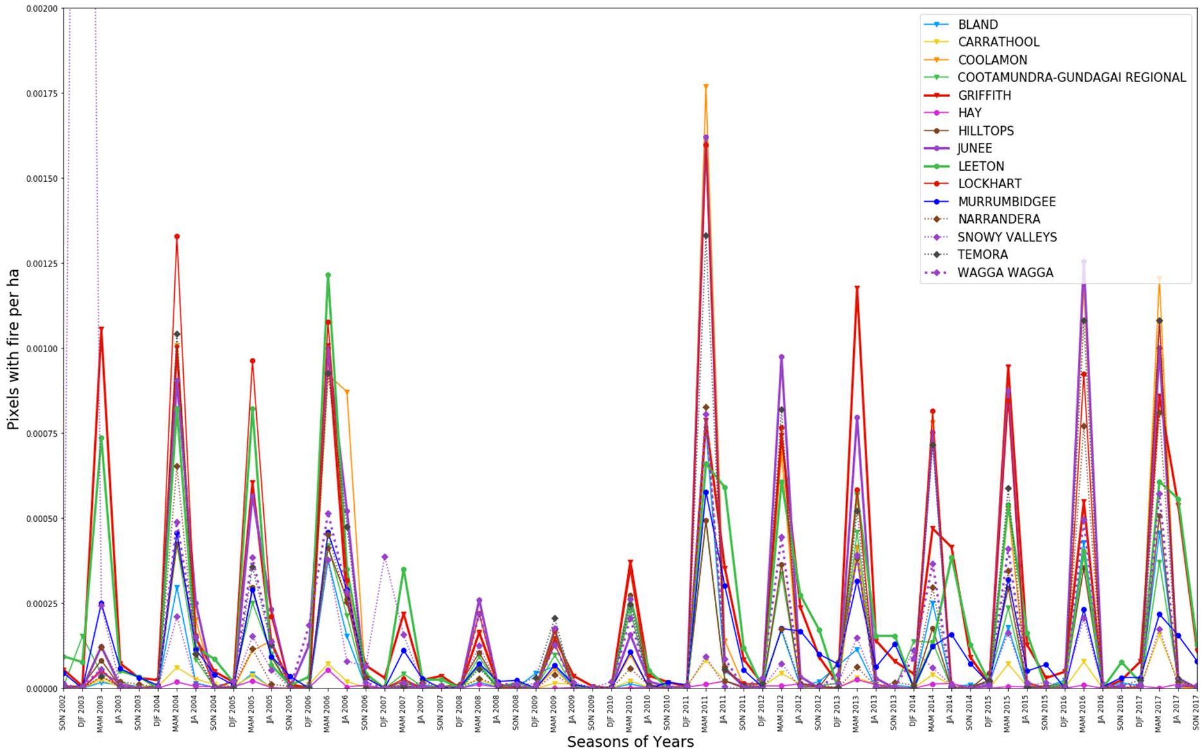


**Figure 7.4.** Time-series of seasonal densities of pixels with fire for each Riverina LGA. SON 2002 to SON 2017. Snowy Valleys obtained a maximum value of 0.005833$^{-ha}$ in DJF 2002-2003.

### 7.3.3 Land use

As established in previous chapters, The Riverina is located within the southern NSW extent of the Wheat-Sheep Belt and dominated by areas of Dryland Cropping. The spatial distribution of land uses varies across the LGAs, reflecting the rainfall and topographic gradients present. Irrigation has also been introduced into the western semi-arid regions (Figure 7.5).

Grazing on native vegetation was widespread in the western extent, encompassing much of Hay and extending into broad areas within Carrathool and Murrumbidgee. Grazing on modified pastures, on the other hand, was more common towards the slopes in the east, as are much of the forestry and conservation areas. Irrigated Cropping areas are densely clustered around Murrumbidgee, Griffith and Leeton, though extend along the Murrumbidgee River and through the north of Carrathool to the Lachlan River.

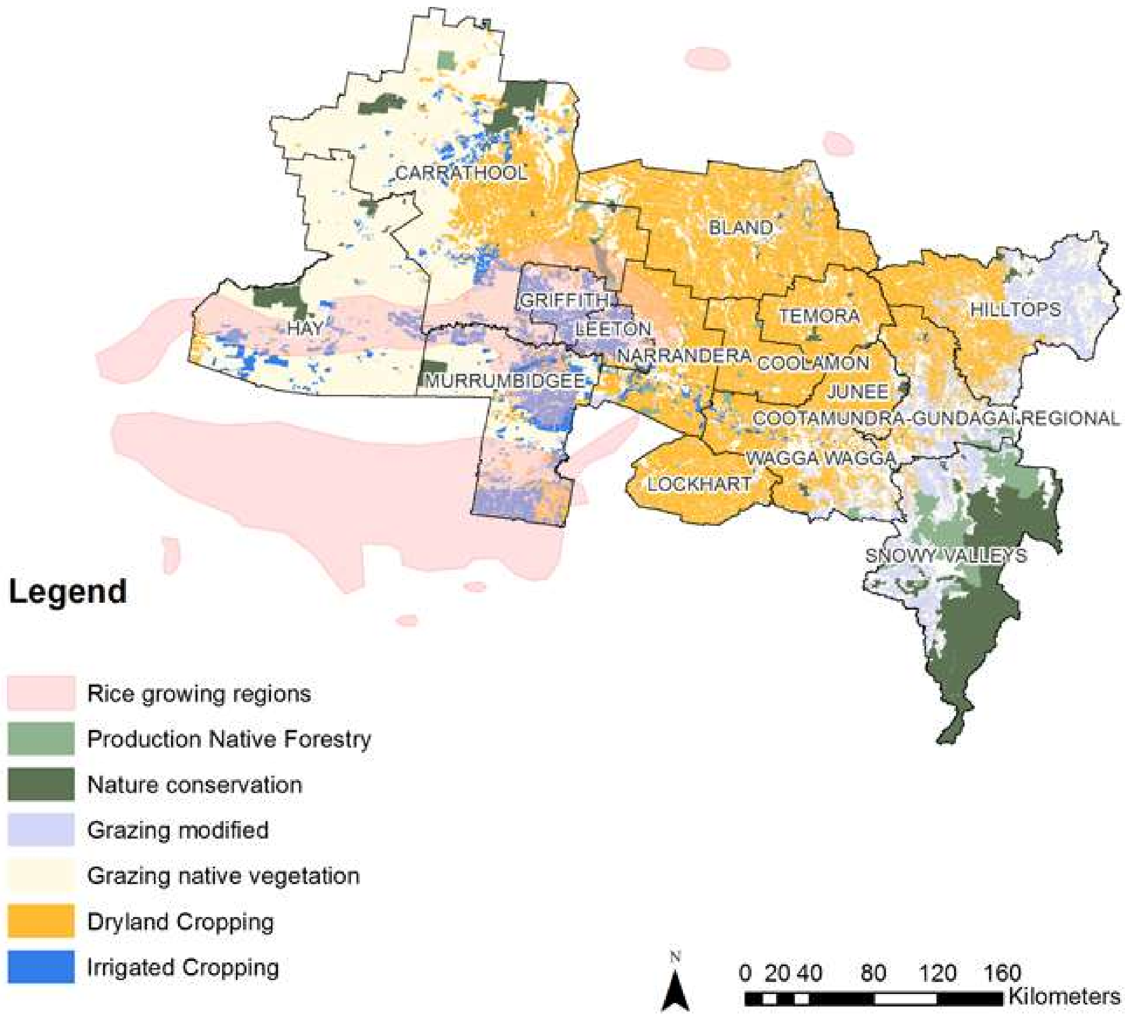


**Figure 7.5.** Map of primary land uses within Riverina LGAs (2013). A pink overlay represents rice growing regions as identified by Sivapalan et al. (2007).

An overlay of rice growing regions, adapted from Sivapalan et al. (2007), encompasses the Murrumbidgee Irrigation Area, the Coleambally Irrigation Area and the Murray Irrigation District to the southwest of the Riverina. Dominant rice growing localities within the Riverina LLS include, Griffith, Leeton, Murrumbidgee, Narrandera. Irrigation is being used by other cropping enterprises concentrating on cotton with rotation of corn. These enterprises are occurring along the Murrumbidgee and further west into the semi-arid Hay plain.

LGAs within the region have variable proportions of land uses. Whilst Griffith and Leeton are regarded as the 'irrigated rice' centres of the Riverina, Irrigated Cropping comprises only 55% and 49% of the shire area respectively (Figure 7.6). Murrumbidgee, despite spanning a larger area, consisted of approximately 30% Irrigated Cropping, 56% grazing, 10% Dryland Cropping and the remainder being reserve/modified pasture grazing. Dryland Cropping dominates the region with half of the LGAs having greater than 50% of their area under dryland cropping. Bland, Coolamon, Junee, Lockhart and Temora each had greater than 75% area under Dryland Cropping (Figure 7.6). Snowy Valleys was distinct from all LGAs in consisting of 45% Nature Conservation area.

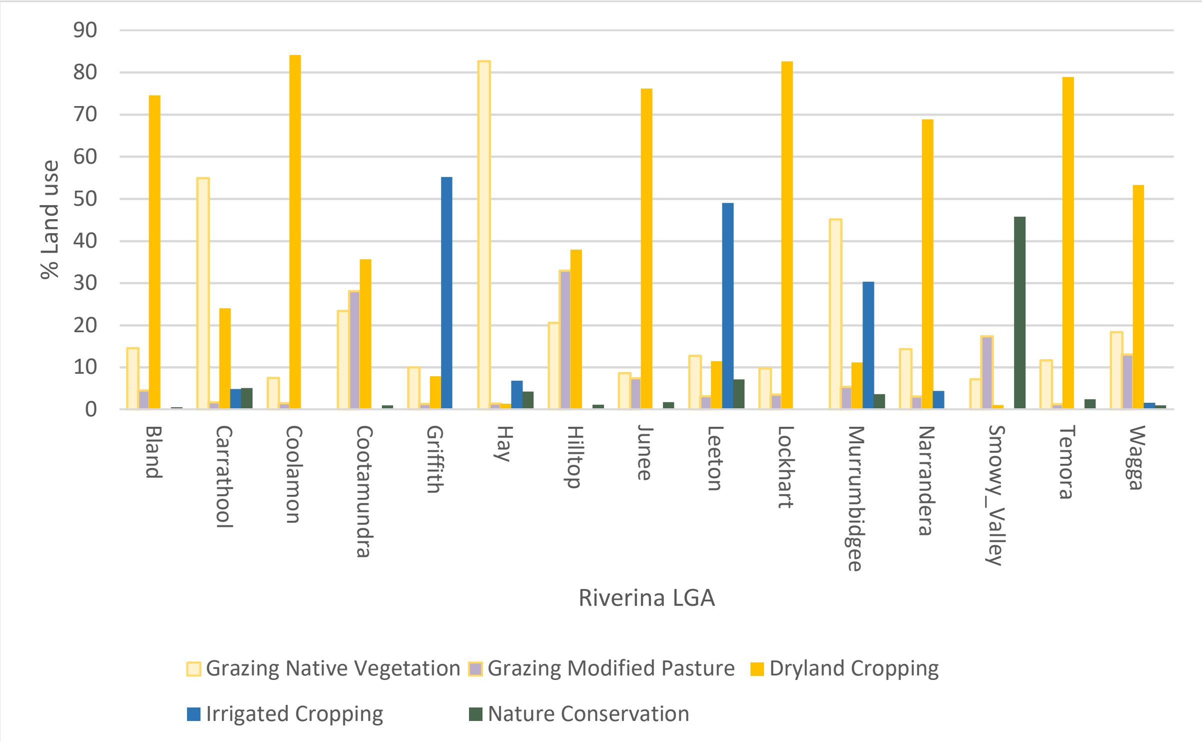


**Figure 7.6.** The percentage area occupied by major Riverina land uses for each Local Government Area, 2013.

### 7.3.4 Changes to cropping land use 2007-2013

**Table 7.1.** Land use differences in Riverina LGAs between 2007 and 2013 (Dryland and irrigated cropping only)

| LGA | ALUM7 | Land Use Description | 2007_ha | %ofLGA | 2013_ha | %ofLGA | Difference_ha | increase % | % inc of LGA |
|---|---|---|---|---|---|---|---|---|---|
| Bland | 330 | Dryland | 339,516.31 | 39.68 | 637,553.11 | 74.52 | 298,036.80 | 87.78 | 34.83 |
| | 430 | Irrigated | 178.72 | 0.02 | 581.04 | 0.07 | 402.32 | 225.11 | 0.05 |
| Carrathool | 330 | Dryland | 333,073.84 | 17.59 | 454,408.28 | 24.00 | 121,334.44 | 36.43 | 6.41 |
| | 430 | Irrigated | 32,500.77 | 1.72 | 91,462.18 | 4.83 | 58,961.41 | 181.42 | 3.11 |
| Coolamon | 330 | Dryland | 140,894.30 | 57.98 | 204,399.36 | 84.11 | 63,505.05 | 45.07 | 26.13 |
| | 430 | Irrigated | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cootamundra | 330 | Dryland | 51,780.14 | 13.01 | 141,798.66 | 35.62 | 90,018.52 | 173.85 | 22.61 |
| | 430 | Irrigated | 0.00 | 0.00 | 497.22 | 0.12 | 497.22 | - | 0.12 |
| Griffith | 330 | Dryland | 6,184.41 | 3.77 | 12,911.38 | 7.88 | 6,726.97 | 108.77 | 4.10 |
| | 430 | Irrigated | 49,723.76 | 30.34 | 90,438.22 | 55.19 | 40,714.45 | 81.88 | 24.84 |
| Hay | 330 | Dryland | 4,156.69 | 0.37 | 14,950.39 | 1.32 | 10,793.70 | 259.67 | 0.95 |
| | 430 | Irrigated | 31,369.99 | 2.77 | 77,765.16 | 6.87 | 46,395.18 | 147.90 | 4.10 |
| Hilltop | 330 | Dryland | 143,314.50 | 20.07 | 271,002.95 | 37.95 | 127,688.45 | 89.10 | 17.88 |
| | 430 | Irrigated | 0.00 | 0.00 | 206.71 | 0.03 | 206.71 | - | 0.03 |
| Junee | 330 | Dryland | 75,091.47 | 36.99 | 154,609.48 | 76.16 | 79,518.01 | 105.89 | 39.17 |
| | 430 | Irrigated | 0.00 | 0.00 | 69.04 | 0.03 | 69.04 | - | 0.03 |
| Leeton | 330 | Dryland | 6,240.79 | 5.35 | 13,418.99 | 11.50 | 7,178.19 | 115.02 | 6.15 |
| | 430 | Irrigated | 23,750.92 | 20.35 | 57,194.14 | 49.00 | 33,443.22 | 140.81 | 28.65 |
| Lockhart | 330 | Dryland | 137,191.79 | 47.39 | 239,080.18 | 82.58 | 101,888.39 | 74.27 | 35.19 |
| | 430 | Irrigated | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Murrumbidgee | 330 | Dryland | 45,598.15 | 6.63 | 76,618.38 | 11.13 | 31,020.23 | 68.03 | 4.51 |
| | 430 | Irrigated | 66,476.70 | 9.66 | 208,701.76 | 30.33 | 142,225.06 | 213.95 | 20.67 |
| Narrandera | 330 | Dryland | 187,839.66 | 45.63 | 283,378.42 | 68.83 | 95,538.76 | 50.86 | 23.21 |
| | 430 | Irrigated | 7,966.83 | 1.94 | 18,105.28 | 4.40 | 10,138.46 | 127.26 | 2.46 |
| Snowy Valley | 330 | Dryland | 1,033.82 | 0.12 | 9,570.28 | 1.07 | 8,536.46 | 825.72 | 0.95 |
| | 430 | Irrigated | 119.18 | 0.01 | 216.99 | 0.02 | 97.81 | 82.07 | 0.01 |
| Temora | 330 | Dryland | 119,209.07 | 42.54 | 221,160.36 | 78.91 | 101,951.29 | 85.52 | 36.38 |
| | 430 | Irrigated | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Wagga | 330 | Dryland | 93,578.77 | 19.39 | 256,901.11 | 53.24 | 163,322.34 | 174.53 | 33.85 |
| | 430 | Irrigated | 2,695.60 | 0.56 | 7,461.02 | 1.55 | 4,765.43 | 176.79 | 0.99 |

Between 2007 and 2013, all Riverina LGAs experienced growth in areas attributed to Dryland Cropping (Table 7.1). Within the same period, all LGAs originally containing Irrigated Cropping also experienced increases. The largest increase to Dryland Cropping took place in Hilltop, which expanded 127,688.45 ha, however this accounted for only a 17.88%

of the LGA. The highest increase in proportion to LGA area was in Junee, which expanded 79,518.01 ha, equating to 39.17% of the LGA. The largest increase to Irrigated Cropping occurred in Carrathool (58,961.41 ha), which amounted to 3.11% increase. The addition of 33,443.22 ha in Leeton, however, resulted in 28.65% growth in area, making it the area of highest proportional growth, above Griffith which increased by 24.84%.

### 7.4 Discussion

The LGAs within the Riverina represent the finest scale of the current study and therefore provide the smallest scale of management drivers in this study. Though the distribution of land uses varies between LGAs, broad spatial associations are apparent, resulting in degrees of uniformity within select areas. Grazing on native vegetation is widespread in the drier western extent, encompassing much of Hay and extending into broad areas within Carrathool and Murrumbidgee. Grazing on modified pastures, on the other hand, is more common in the east, where rainfall is enhanced by orographic lift (abs.gov.au, 2012). Similarly, the majority of land devoted to nature conservation and forestry was found to be concentrated to the southeast, within the Snowy Valleys LGA where rainfall and topography are both higher.

Climate patterns across the Riverina LGAs is an important determinant of land use which in turn drive fire frequency. However, the effects of climate on fire frequency within the LGAs remains largely indirect. The Riverina as a whole is representative of extensive agricultural management and production on modified lands. Concentrated areas of irrigation within the region embody a managed resistance to the effects of climate and climate variability. It will be later shown that the influence of economic factors outweighed that of local climate conditions in irrigated regions throughout the ‘Millennium Drought’.

Furthermore, profiles of distinct and regular fire seasonality associated with cropping indicate all but one of the Riverina LGAs to conform to patterns indicative of human ignition sources.

The contrast in fire occurrence between the Snowy Valleys and the other LGAs continued to highlight the differences of seasonality, recurrence and magnitude between land uses associated with high and low wildfire risk. Mean annual detections for Snowy Valleys reflected the powerful and disproportionate influence of the 2002-2003 South East Australian bushfires, which were ignited by lightning and affected broad areas of south-eastern NSW during DJF (Taylor and Webb, 2005). Nearby LGAs containing large areas of Dryland Cropping, such as Hilltop, Lockhart and Wagga Wagga, instead displayed regular high-level burning isolated to MAM. Areas characterised by broad-scale Irrigated Cropping also associated with a strong MAM seasonality though exhibited residual activity in the proceeding months, consistent with state level observations, established in Chapter 6.

The greatest fire frequencies between Riverina LGAs were found to occur within Griffith and Leeton. Both LGAs clearly dominated by irrigated cropping and situated within the rice growing Murrumbidgee Irrigation Area. Somewhat counterintuitively, the more extensive Murrumbidgee LGA, which is intersected by three rice growing irrigated regions, ranked only moderately in fire frequency.  This may be explained by the prevalence of grazing land within the LGA, as indicated by Figures 7.5 and 7.6. As established in the previous chapter, Grazing Native Vegetation presents substantially lower rates of fire frequency when compared with other dominant land uses. Despite recording higher overall fire detections than Griffith and Leeton, high fire frequencies associated with Irrigated Cropping within the Murrumbidgee LGA were undoubtedly offset by the low fire frequencies linked with grazing.

The Junee, Lockhart and Coolamon LGAs rank lower than Griffith and Leeton in fire frequency and each represent smaller areas proportionately high in Dryland Cropping land use. Bland, Wagga Wagga and Hilltop boasted more extensive coverage of Dryland Cropping in 2013 (Table 7.1), however, like Murrumbidgee, both LGAs contained a higher proportion of grazing land uses, contributing to lower fire frequencies. Increases in area attributed to Dryland Cropping in Junee between 2007 and 2013 are paralleled by higher fire densities relative to other LGAs (Figure 7.5).

Trends in fire occurrence and density of fire for all cropping LGAs align with those observed on a state level, displaying a prominent contraction between 2007 and 2010. As established in the prior chapter, high cereal prices in 2007-2008 drove expansion in Dryland Cropping for much of NSW, yet rainfall deficiencies associated with drought resulted in a reduction in yield per unit area, despite widespread water use efficiency practices (van Dijk et al., 2013). The relationships between yield, stubble density and crop residue burning also suggest that lower levels of burning during this period bore a reduced association with cropping area.

Between 1993 and 2006, cropping area increased by more than 10% in all Riverina LGAs, with the exception of Hay and Carrathool (Mewett, 2013). The current study finds substantial increases to have occurred by between the 2007 and 2013 land use datasets (Table 7.1), yet significant limitations identified in the 2007 dataset are likely to have resulted in the overstatement of growth within this period. Source acquisition dates within Riverina LGAs were found to range from 1996 to 2005 in the 2007 dataset. The 2013 dataset by comparison was mostly concurrent with minor instances of aerial photography dated to 2003. Nevertheless, a trend of expansion in cropping land was evident throughout the study period, supported by observations from Kirby et al (2012) and van Dijk et al (2013). This trend is likely to have contributed to greater fire densities observed in the years following the

Millennium Drought. However, the impacts of rainfall deficiencies, evident in Dryland Cropping do not address the reduction of fire activity observed in Irrigated Cropping.

Similar to cereals, the value of rice climbed between 2001 and 2009. However, declining water availability in the Murray Darling Basin, along with the heavy demands for water associated with rice growing, saw water trading as a more lucrative investment for rice growers at the time (Kirby et al., 2012). Subsequently, rice production fell to a low of 18kt[2] in 2007-2008, as water prices peaked and irrigated areas within the Riverina sold water allocations to VIC and SA (Kirby et al., 2012). Unlike Dryland Cropping, reduced fire densities between 2007 and 2010 resulted from limited crop production within the period, rather than yield decreases per unit area. Despite this, Irrigated Cropping area within Riverina LGAs continued to grow between 2007 and 2013, particularly in Leeton, Griffith and Murrumbidgee.

Seasonal fire densities for Leeton, Griffith and Murrumbidgee, following the end of the Millennium Drought and the 2010-2011 La Niña, exhibit a pattern of increased burning in JJA and SON when compared with earlier activity within the study period. It is possible that this activity relates to delays in rice residue burning as a response to local meteorological conditions. The Rice Growers Association of Australia has in recent years run a stubble management awareness program to reduce the effects of smoke to nearby communities and manage public concerns (Bull, 2017). While advice on alternative stubble treatments are offered, many of the strategies suggested involve the considered timing of burns in relation to wind velocity, atmospheric inversion and fuel moisture (Bull, 2017). Currently, however, this remains speculatory and requires further study to ascertain whether patterns are representative of pre-drought conditions or a result of the conflict between increases in Irrigated Cropping area and pressures to maintain acceptable levels of air quality.

# Chapter 8: Conclusions

This thesis has argued land use to be a predeterminant of fire frequency within rural NSW by the provision of spatial and temporal analysis over various scales. It has provided evidence of a profound influence from management practices, governed by land use, on the distribution, magnitude and seasonality of fire activity within the state. This was most notable within the highly fire-prone Riverina region, which was determined to be a considerable influence on state level total fire detections, as well as the producer of the highest fire frequencies within NSW.

Climate also remains an important and influential facet of the potential for fire to occur on all spatial and temporal scales, primarily as a result of rainfall distribution. Its influence on the production of vegetation biomass, as well as the conditioning to dry fuel is epitomised by the intensely burnt savanna of the tropical north, but extends to all scales as land use distribution itself is inherently linked to climate. However, the realisation for the potential provided by accumulated fuels is predominantly limited by ignitions.

Managed burning, according to the requirements of land use, acts as a primary source of ignitions for many land uses. Despite this, unmanaged fire remains powerfully apparent in relatively unmodified lands predisposed to wildfire, such as native conservation and native forestry. Evidence suggestive of managed burning activities were also observed within these land uses, yet found to differ in application as indicated by fire density values in low wildfire risk seasons.

Fire associated with dryland and irrigated cropping was found to adhere to a pronounced MAM seasonality, consistent across many regions displaying high fire frequencies and total fire occurrence. Within the Riverina, the highest fire frequencies were produced by irrigated cropping areas, consistent with state level land use observations.

Conversely, total fire occurrence within the region was determined to be driven by dryland cropping, which displayed lower fire frequencies, though covered a more extensive, and increasing area.

To the author's knowledge, no other work has attempted to explore the interactions of fire and multiple land uses at the range of spatial scales or extent of sampling period employed. Many studies have investigated the influence of climate on the occurrence and distribution of fire activity in wildfire-prone regions and biomes, while others have focused on fire occurrence within specific land uses, or drawn comparisons between land management applications within localised areas.

This thesis offers a unique perspective of fire within the NSW landscape, as it pertains to multiple land uses. Furthermore, it has identified regions and seasons of concern, where losses to groundcover are likely to exacerbate existing erosion risks and isolated a rise in state wide burning activity to the expansion of dryland cropping in the Riverina LLS.

Recommendations for further study include investigation into the potential calibration of contemporary fire detection products, such as VIIRS, with MODIS to ensure continued and consistent monitoring of fire and land use dynamics, as well as the potential community impacts of smoke relating to increased residue burning from within the Riverina.

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# APPENDIX A.

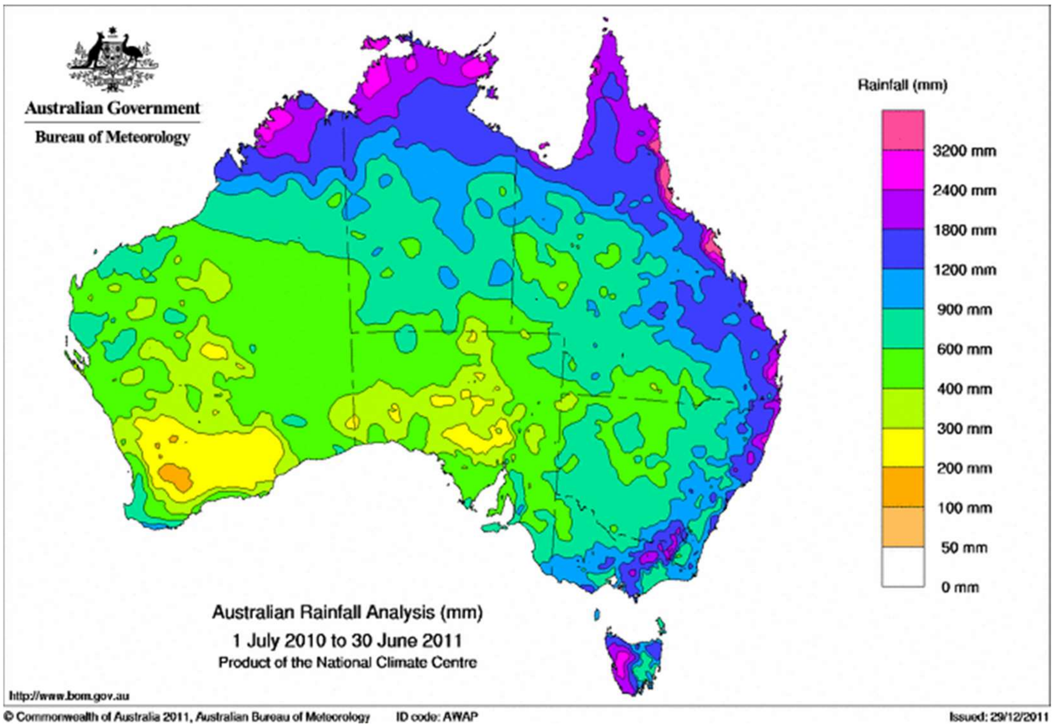


**Figure A1**. Australian annual rainfall, 1 July 2010 to 30 June 2011. Sourced from bom.gov.au

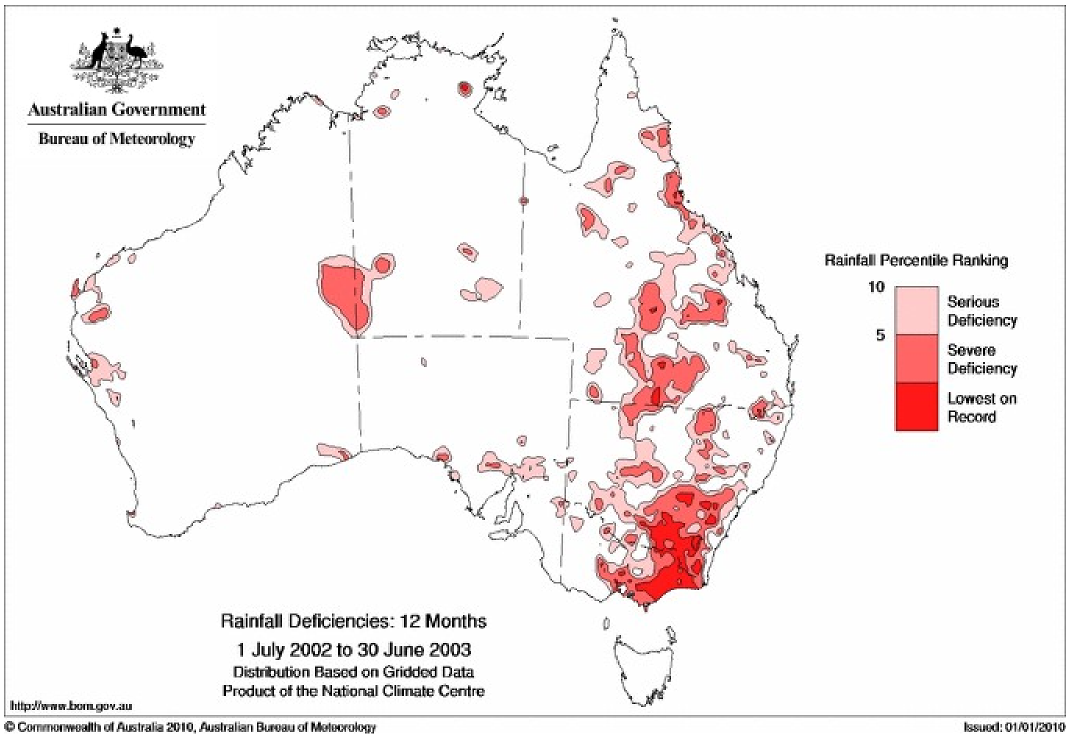


**Figure A2.** Australian rainfall deficiency, 1 July 2002 to 30 June 2003. Sourced from bom.gov.au

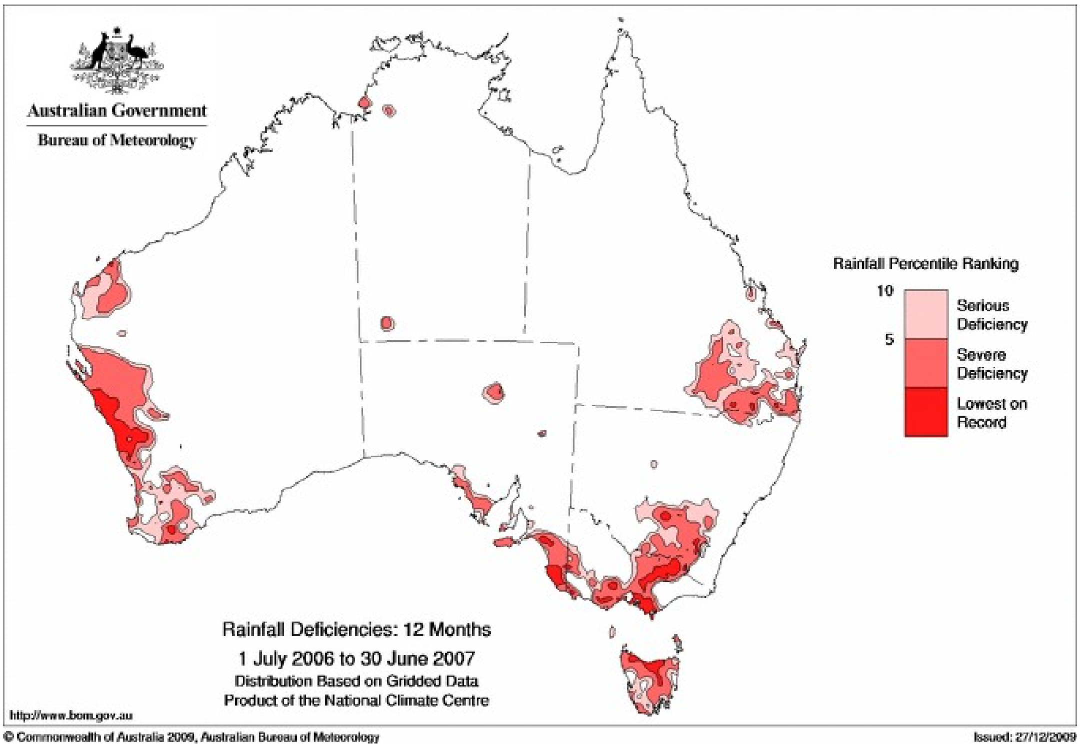


**Figure A3**. Australian rainfall deficiency, 1 July 2006 to 30 June 2007. Sourced from bom.gov.au

# APPENDIX B.

Table 1. Australian State mean values of pixels with fire detection (2003-2017)

| State | Total annual | Frequency ($ha^{-1}$ $y^{-1}$) |
|---|---|---|
| ACT | 141.67 | 0.000601 |
| NSW | 13,250.33 | 0.000165 |
| NT | 94,882.93 | 0.006634 |
| QLD | 63,836.80 | 0.000356 |
| SA | 4,187.93 | 0.000042 |
| TAS | 1,561.13 | 0.000223 |
| VIC | 7,191.60 | 0.000315 |
| WA | 72,394.33 | 0.00028 |

Table 2. NSW LLS mean values of pixels with fire detection (2003-2017)

| NSW LLS | Total annual mean | Frequency ($ha^{-1}$ $y^{-1}$) |
|---|---|---|
| Central Tablelands | 543.07 | 0.000174 |
| Central West | 1,712.13 | 0.000187 |
| Greater Sydney | 264.87 | 0.000215 |
| Hunter | 605.40 | 0.000184 |
| Murray | 1,433.80 | 0.000342 |
| North Coast | 1,194.27 | 0.000372 |
| North West NSW | 1,604.67 | 0.000194 |
| Northern Tablelands | 1,192.20 | 0.000301 |
| Riverina | 2,539.73 | 0.000379 |
| South East NSW | 1,422.73 | 0.000256 |
| Western | 737.47 | 0.000023 |

Table 3. Riverina LGA mean values of pixels with fire detection (2003-2017)

| Riverina LGA | Total annual mean | Frequency (ha$^{-1}$ y$^{-1}$) |
|---|---|---|
| BLAND | 215.07 | 0.000251 |
| CARRATHOOL | 132.60 | 0.00007 |
| COOLAMON | 168.47 | 0.000693 |
| COOTAMUNDRA-GUNDAGAI REGIONAL | 131.47 | 0.00033 |
| GRIFFITH | 149.27 | 0.000911 |
| HAY | 31.40 | 0.000028 |
| HILLTOPS | 243.00 | 0.00034 |
| JUNEE | 160.33 | 0.00079 |
| LEETON | 93.00 | 0.000797 |
| LOCKHART | 225.60 | 0.000779 |
| MURRUMBIDGEE | 283.27 | 0.000412 |
| NARRANDERA | 150.33 | 0.000365 |
| SNOWY VALLEYS | 563.07 | 0.000628 |
| TEMORA | 186.87 | 0.000667 |
| WAGGA WAGGA | 215.60 | 0.000447 |