A review of the effect of farming practices, including continuous cropping, minimum tillage and direct drilling, on bushfire risk and prevention

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THE UNIVERSITY OF MELBOURNE

bushfire CRC

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Primary Industries and Resources SA

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A review of the effect of farming practices, including continuous cropping, minimum tillage and direct drilling, on bushfire risk and prevention

A report prepared for the Minister for Emergency Services (acting through the South Australian Research and Development Institute) under contract with the University of Melbourne (in association with the Bushfire Cooperative Research Centre)

Authors:

Dr Kevin Tolhurst (University of Melbourne, Bushfire CRC, Creswick, Vic.)
James Egan (South Australian Research and Development Institute, Port Lincoln, S.A.)
Thomas Duff (University of Melbourne, Creswick, Vic.)

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Executive Summary

This review has highlighted that while grassfires have been the focus of a reasonable amount of research, there have been no specific studies focusing on wildfires in crops and crop residues under different management practices.

On the balance of the evidence presented in this review, the greatest change to fire risk through recent farming trends and changed practices has resulted from the intensification of cropping and the associated reduction in livestock grazing not the use of conservation tillage *per se*. This has led to a more continuous pattern of fire fuels across the landscape, providing greater potential for fire to become large and more severe.

Other trends and changes in farming practices that have exacerbated the fire risk include:

- Reduced cultivation of paddocks over summer and autumn for weed control, moisture conservation and seedbed preparation;
- Larger paddock sizes;
- Fewer cultivated, sprayed or mown firebreaks within paddocks;
- Higher crop yields and hence fuel loads.

Adoption of the sowing techniques of minimum tillage and direct drilling *per se* have most likely not increased the fire risk, since the cultivations normally associated with traditional sowing techniques are most often not undertaken until autumn, by which time the peak fire danger has passed.

It is expected that there are significant differences in the fire behaviour in cereal crops and stubbles compared with canola and pulse crops, due to their different conformation, stalk dimensions, spatial density and energy values, but no reports of such experimental comparisons could be found.

Farming practices with potential to reduce fire risk include:

- Strategically located firebreaks, as cultivated, sprayed or mown strips, and heavily grazed areas;
- Windrowing crops prior to harvest;
- Hay paddocks;
- Grazing crop stubbles;
- Baling cereal straw;
- Harvest management to reduce stubble height, such as straw choppers or spreaders on headers;
- Post-harvest stubble management, such as rolling, chaining, harrowing or slashing.

Spatially explicit consideration of cropping and land management practices may allow some amelioration of increased fire risks, but further research is needed to highlight vulnerabilities and assist with strategy development.

This review has identified significant knowledge gaps in the management and risks posed by current farming practices. In order to make informed decisions in managing fires at a landscape level on Lower Eyre Peninsula and similar agricultural regions of southern Australia, further research should address the following issues:

- The effects of seasonality, crop species and yield on fire behaviour under various scenarios;
- Characterization of different crop types (i.e. cereals, oilseeds and pulses) in terms of their fuel surface area-to-volume ratios, fuel gap size, and degree of continuity and fuel loads;
- Seasonal and annual trends in fuel properties in cropping districts in relation to fire weather;
- The effects of conservation farming practices on fuel properties including fuel retention, breakdown and soil mulches;
- Potential uses and markets for cropping residues including grazing and baled straw;
- Strategic landscape management, including optimisation of paddock sizes, firebreaks, crop layouts, species mixes, grazing levels;
- Future requirements for fire detection, management and suppression based on expected trends.

It should be stressed that any changes to farming practices to minimise fire risk, whether recommended or mandated, should undergo critical analysis to determine the real benefits and the full costs of adoption.

1.0 Terms of Reference

This literature review addresses two recommendations from the Coronial Inquiry (29.9.2 & 29.9.3) into the Wangary Fire of 2005 (Schapel, 2007, p.579). These recommendations concern the need to: "… *cause independent scientific or other research to be undertaken to identify the effects of continuous cropping, minimum tillage, direct drilling seeding practices and of the retention of cropping stubble, in respect of bushfire risk and prevention*." (Coronial Finding, 29.9.2), and secondly, *"… cause independent scientific or other research to be undertaken to establish means by which risk of bushfires, as created by continuous cropping, minimum tillage, direct drilling seeding practices and the retention of cropping stubble across the landscape can be minimised.*" (Coronial Finding, 29.9.3).

This review focuses primarily on the cropping practices and the crop species that are predominant on the Lower Eyre Peninsula of South Australia and the potential effects different options may have on fire behaviour. Land management techniques and cropping practices and trends on the Lower Eyre Peninsula are similar to those employed in other agricultural regions of southern Australia, so the findings in this review are likely to be pertinent to the broad region of cropping land across much of southern Australia. No specific fire behaviour research has been undertaken in croplands, so this review will use results from grassland fire research and apply it as far as is possible to the cropland situation.

The objective of this review is to summarize the existing body of knowledge concerning fire spread and mitigation in pasture and cropland and to identify areas requiring further research.

2.0 Introduction

On January 11, 2005, an extreme bushfire event swept across the Lower Eyre Peninsula region in South Australia. The fire burnt through approximately 78,000 hectares, about 80% of which was highly productive agricultural land used for cereal, oilseed and pulse grain production and extensive livestock grazing on improved pastures. Nine lives were lost in the fire, leading to a Coronial Inquest being held. Two recommendations in the Coroner's report called for a review of land management practices on Lower Eyre Peninsula, in terms of the impact of changed practices in recent years on bushfire risk and prevention. In particular, the Coroner recommended that the practices of continuous cropping, minimum tillage, stubble retention and direct sowing should be investigated, in conjunction with techniques (such as ploughing paddocks and firebreaks after harvest) to minimise the fire risk (Schapel 2007).

Changes in cropping practices affect a number of factors that can impact of the behaviour of wildfire in agricultural crops, affecting the way fires spread in a landscape and the chances of rapid suppression. Conservation farming practices such as direct drill sowing, minimum tillage and stubble retention are being more widely adopted (Adcock, 2005), as they have the potential to provide a range of benefits including reduced soil erosion, reduced compaction, increased nutrient levels, and improved soil structure, biology and water holding capacity. The intent of these practices is to leave more of the crop residues in the paddock and in particular on the soil surface to provide soil protection. At the same time, there has been a steady move to more intensive cropping systems, with paddocks cropped more frequently or even continuously, and a consequent reduction in numbers of livestock carried on farms. To date, there have been no comprehensive studies on the effects of intensive cropping systems with conservation tillage techniques on fire risk and behaviour.

Bushfires are a frequent occurrence in south-eastern Australia and pose a challenge to land management in order to minimise impacts and facilitate suppression. Grassfires play a significant role in the spread and destructiveness of bushfires, and are considered to be the direct cause of most damage to private property (Cheney & Sullivan, 1997). Grassfires have the potential to spread much more quickly and erratically than fires in heavier vegetation types (Luke & McArthur, 1978; Noble, 1991), posing significant difficulties in the suppression of fires in mixed vegetation types. Fires within agricultural crops and crop residues can be considered a type of grassfire, as the physical properties are comparable, and winter crops undergo a similar process of curing before harvest. The management of fires within crops is important as they have major economic value and also the potential to facilitate the spread of bushfires between forested areas (Luke & McArthur, 1978).

3.0 Fire behaviour in grasslands including pastures and crops

Wildfires in pastures and grain crops in south-eastern Australia have caused major social and economic losses in the past (Cheney & Sullivan, 1997). The ability to predict the spread of fires in grasses and crops is an important factor in the management of risk and minimisation of losses due to bushfire. There is a considerable body of research supporting fire behaviour in grasslands (Anderson, 1982; Cheney & Gould, 1995; Cheney, Gould, & Catchpole, 1993, 1998; Cheney & Sullivan, 1997; Clements *et al*., 2007; Mell, Jenkins, Gould, & Cheney, 2007; Parrot, 1964; Scott & Burgan, 2005; Sneeuwajagt & Frandsen, 1977), although there has been very limited work assessing fire behaviour in crops and crop residues. Crops fires can be considered to be a class of grassfire (Cheney *et al*., 1998).

The main methods for predicting grassfire behaviour in Australia are through the use of the Mark 4 Grassland Fire Danger Meter (I. R. Noble, Bary, & Gill, 1980) and the CSIRO Grassland Fire Spread Meter (Cheney & Sullivan, 1997). The Mark 4 Grassland Fire Danger Meter provides a measure of fire danger, the Grassland Fire Danger Index (GFDI). This relates to the probability of fire ignition, spread rates and difficulties of suppression (Table 1).

Table 1: Grassland Fire Danger Rating and difficulty of suppression in an average pasture of 4 t/ha (oven dry weight).

Fire Danger Rating	Fire Danger Index (GFDI)	Difficulty of suppression
Low	1-2.5	Low. Head fires stopped by roads and tracks.
Moderate	2.5-7.5	Moderate. Head fire easily attacked with water.
High	7.5-20	High. Head fire attack generally successful with water.
Very High	20-50	Very high. Head fire attack may succeed in favourable circumstances. Backburning at close to fire head may be necessary.
Extreme	>50	Direct attack of the head fire will fail. Back burns from a road for wide fireline will be difficult to hold because of blown embers. Systematic attack from the rear up along the flanks is usually successful.

Source:(Gould, 2005)

The CSIRO Grassland Fire Spread Meter provides a direct estimate of the average rates of headfire spread under specified fuel, weather and slope conditions. Short-term variation in rates of spread is high as grassfires respond rapidly to small variations in factors such as slope, curing, fuel continuity and wind gusts.

Four factors affect fire behaviour: fuel, weather, topography and the nature of the fire itself.

3.1 Weather and seasonal conditions

Weather and seasonal conditions are key determinants of fire behaviour, and are conditions that cannot be controlled. Underlying drought conditions are important to any major fire event. The drought may be a result of an annual cycle where rain has not occurred for a number of weeks or it may result from a prolonged run of significantly below average rainfall years. Where grassland and crops are concerned, it is the annual period of drought that is most important because this means that there is potentially a high level of fuel available from good winter or spring growth now made available by a dry summer or autumn period.

Of the short-term weather conditions, wind speed has been found to be the single most important factor in determining grassland fire behaviour (Cheney & Sullivan, 1997; Scott & Burgan, 2005; Sneeuwjagt & Frandsen, 1977). Fire spread rates are directly related to wind speed (Figure 1), but there is a threshold (5 km/h) below which fires will not spread consistently (Cheney & Sullivan, 1997).

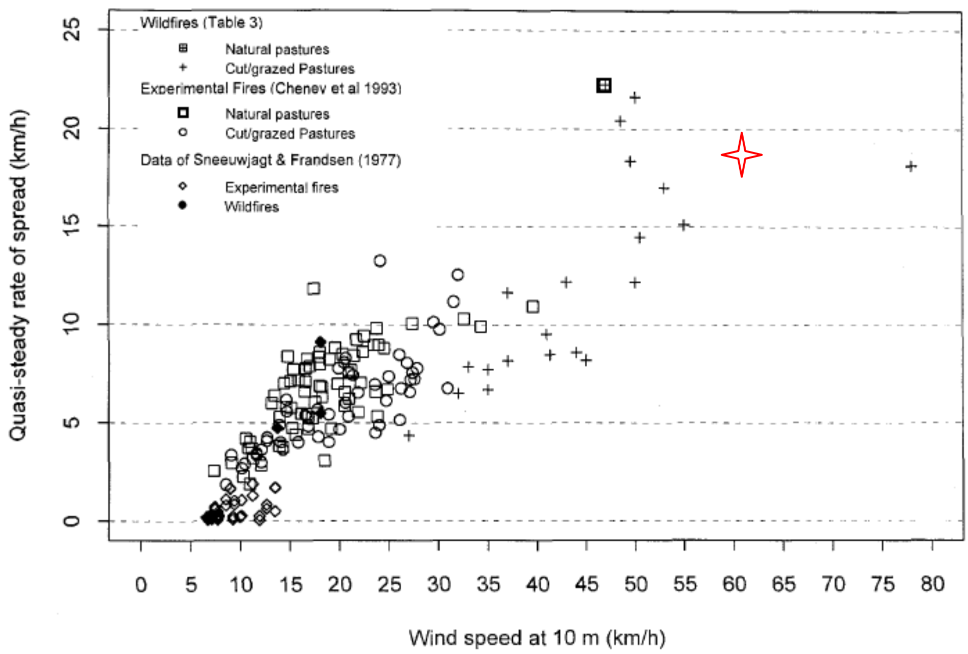

Figure 1: Relationship between wind speed and fire spread rates. **Source: (Cheney *et al*., 1998). The red star represents the average rate of spread of the Wangary fire before noon on 11th January (Gould 2005).**

Grassfires are very responsive to changes in wind, so variation in wind speed and direction can have significant implications for fire control. Fires are driven in the direction of the wind, with high winds reducing lateral and backward spread resulting in a narrower, more linear fire shape. Other environmental factors which affect grassfire behaviour are landscape slope and air relative humidity. Fire spread rates are proportional to slope, with increased fire behaviour due to convective preheating of fuels (Luke & McArthur, 1978). Relative humidity affects fuel moisture content. The effects of fuel moisture on fire behaviour will be discussed as part of fuel properties.

3.2 Fuel properties

Fuel properties are directly related to crop management practices, and changes in practices, such as the introduction of conservation tillage, more intensive cropping and less grazing, can significantly impact how a fire will behave at a specific time. The major fuel related properties that influence grassfire behaviour are fuel moisture content and fuel physical structure.

Fuel moisture content

Fuel moisture content (FMC) is the average amount of moisture in grass fuels, measured as a percentage of oven dried weight. This includes water held within plant cells, so FMC can vary from 2 to 200% of the plant's dry weight. FMC affects a range of properties in relation to fire behaviour and is the key determinant of ignitability. A fuel moisture content of less than 15% is required for ignition (Luke & McArthur, 1978), and fires rarely occur where moisture content is greater than this unless greater windspeeds are present to sustain fire spread (O'Bryan, 2005). Along with wind speed, FMC is one of the most important determinants of the rate of spread of grassfires (Figure 2).

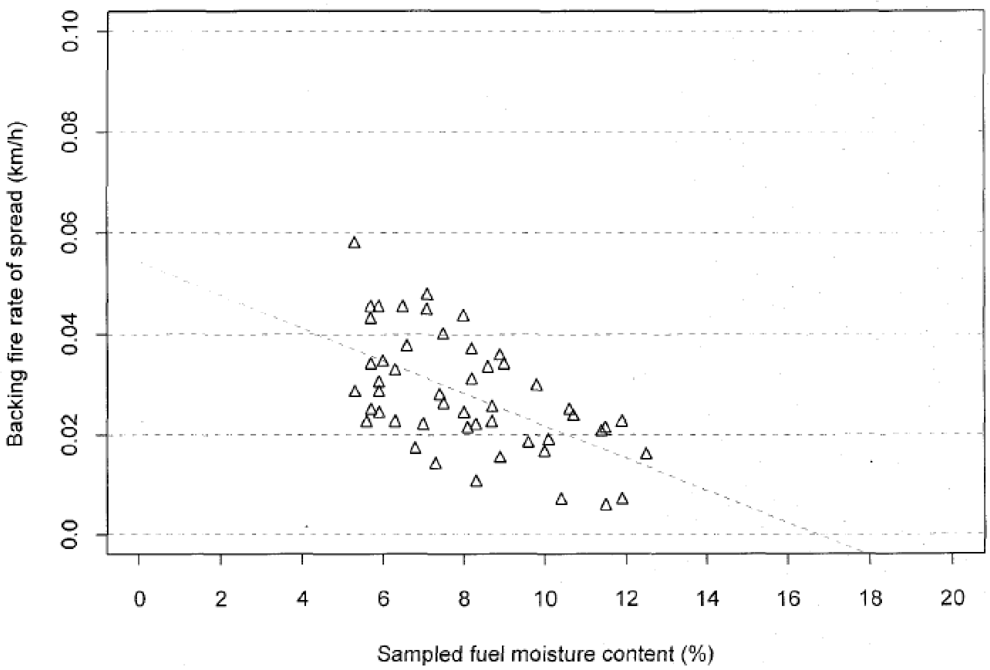

Figure 2: Backing fire rate of spread in grasslands at different moisture contents. Source: (Cheney *et al*., 1998).

Within crops, FMC is affected by two main properties: the degree of curing and the moisture content of dead fuels. The degree of curing is the percentage of dead material within a crop (Cheney & Sullivan, 1997). Grain crops grown on Lower Eyre Peninsula go through a curing process in the lead up to harvest, whereby the moisture content of crops progressively declines and the proportion of dead material increases. Curing timing varies between crop species and varieties, and is a function of the temperatures and water availability in the time leading up to harvest (Baxter & Woodward, 1999; Kemanian *et al*., 2007). Harvest occurs between 90 and 100% curing. Figure 3 shows the progression of grass curing that occurs during the spring-summer period in south-eastern Australia. Annual winter grain crops would show a similar trend.

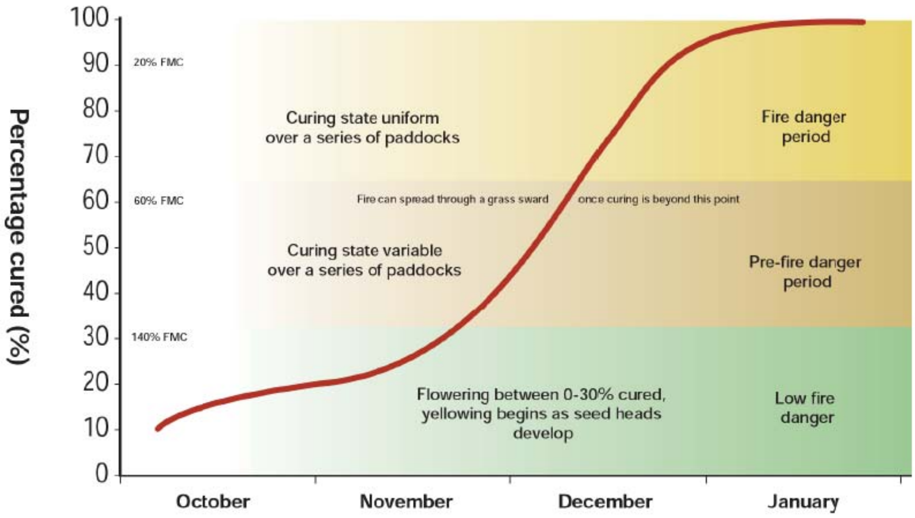

Figure 3: **Progression of curing over the summer period in south-eastern Australia. (Source: CFA, 1999).**

Crops are generally not harvested until the moisture content drops below about 13 to 14%, the level at which grain can be delivered into the commercial grain storage and handling system. Farmers then tend to harvest as soon as possible once moisture levels drop below this threshold, to prevent grain loss (due to fire, shattering or knockdown) or quality downgrading (due to moisture staining, sprouting or fungal disease).

Thus grain harvest will usually occur when crop moisture is at a level where fires will ignite easily and have the potential to spread rapidly. Harvest machinery working within crops at this period increase the risk of fire ignition (Table 2). The Country Fire Service of South Australia (CFS) reports that statistically, fires caused by harvesting operations usually result in larger fires than those from other causes under the same conditions (CFS, 2008a). The Draft Grain Harvesting Code of Practice, developed by the CFS, requires that grain harvesting operations be suspended when the local actual Grass Fire Danger Index exceeds 35. A GFDI of 35 represents a fire danger class of 'Very High' with a corresponding difficulty of suppression.

Table 2: **Rural wildfires in South Australia between 2002 and 2005.**

Fire Cause (Number)	02/03	03/04	04/05
Harvesting – Material accumulation	12	9	7
Harvesting – Engine or exhaust	5	3	3
Harvesting – Mechanical failure	11	19	28
Harvesting – Static electricity	6	2	9
Harvesting – Other	17	20	12
Total Harvesting caused fires	***51***	***53***	***59***
Total – Rural fires, all causes	***1,645***	***1,375***	***1,459***
% due to harvesting	3	4	4

Source: (CFS, 2008b)

Crops are only likely to be below the critical 15% moisture level for a short period prior to harvest, and then not all crops in a district will be at this stage of curing at the same time. Later maturing crops and varieties, and later sown crops, will mature more slowly and under normal seasonal conditions will not fall below the 15% moisture level until some earlier maturing crops in the district will have been harvested. Thus the potential for disastrous fire movement through ripening crops across the district will be alleviated to some extent by the inherent variability in degree of crop curing. Towards the end of the harvest period, particularly where there are delays to harvest, for example through machinery breakdown, inclement weather or lack of capacity to harvest and deliver grain to storage, the fire risk will be exacerbated due to a high continuity of dry crops and crop residues. Harvesting on Lower Eyre Peninsula typically occurs in November and December, although harvest dates vary between years depending on weather conditions leading up to harvest.

Farming practices that allow continuous cropping have limited effect on the FMC of crops, apart from the retention of fully cured stubble after harvest. The selection of crop species and variety has some influence over curing time, such as early maturing wheat or slower maturing lupin (Egan *et al.*, 2007), although curing differential between crops or varieties is generally limited to 2-3 weeks. Once harvest has commenced, harvest pattern is generally dictated by operational logistics rather than crop maturity. Differences between curing state may affect fire intensity across a landscape at a single point in time, but only very large differences will promote fire suppression during Extreme fire weather conditions around harvesting time. The timing of a wildfire is important in determining the fuel response of unharvested crops.

After harvest, crop residues will be dead and can be assumed to be 100% cured therefore the moisture content of these residues is determined by their temperature and the relative humidity of the air. Due to the high surface area-to-volume ratio of these fuels, the moisture content of the crop residues responds quickly to ambient conditions, becoming very dry very quickly on days of Extreme fire weather (O'Bryan, 2005).

Fuel physical properties

The physical properties of crops are those that can be most easily altered by changing cropping practices. These include fuel load, height, continuity, surface area-to-volume ratio of the fuel elements and bulk density of the fuel bed. There has been limited research into the flammability of different species and varieties of grass fuel, although some inferences can be made based on other research on physical properties.

Surface area-to-volume ratio (fuel elements)

The surface area-to-volume ratio of the fuel elements is an important property of fine fuel because it strongly influences the ease of ignition and burnout time (Anderson, 1970; Fernandes & Rego 1998). There is an inverse correlation between surface area-to-volume ratio and residence time, with longer residence time in thicker fuels (Mell *et al*., 2007). High surface area-to-volume ratios enable high rates of energy and mass exchange during pyrolysis, leading to lower ignition delays and higher rates of fire spread (Chandler *et al*., 1983). The importance of the surface area-to-volume ratio in fire behaviour is reflected in the importance it plays in the fire behaviour model of Rothermel (1972), but has not been explicitly included in Australian fire behaviour models. Much of the work on modelling grassfires has been done with relatively narrow grasses, and Luke and McArthur (1978) note that error in spread predictions for crops may be slightly biased as crops generally have thicker stems and correspondingly lower surface area-to-volume ratios than many grasses. There has been limited research into the differences between fuel types in grassfire type fuels, although a study by Parrot (Parrot & Donald, 1970) hypothesised that differences were primarily due the variation in fuelbed structure and fuel element shape.

Different types of crops and pastures produce fuels with quite different surface area-to-volume characteristics. Cereals on Lower Eyre Peninsula typically produce stems at maturity ranging from 2 to 5 mm diameter, while canola and lupin stems can range from approximately 5 to 12 mm. Thus the surface area-to-volume ratio will be typically greater in cereals than in canola and lupins, making cereal crops and stubbles a potentially higher fire risk than other crops in the region (Figure 4). These differences have not been explored or incorporated into fire behaviour models used in Australia. Some examples of the range of surface area-to-volume parameters reported in the literature are given in Table 3.

Table 3: Some indicative surface area-to-volume ratios for different fuel types.

Material	Mean Diameter (cm)	Average thickness (cm)	Surface-volume ratio (cm^2/cm^3)
Sorghum intrans (N.T.)	0.503	0.050	40
Phalaris tuberosa (long)	0.399	0.051	39
Phalaris tuberosa (short)	0.295	0.036	56
Rye grass (*Lolium rigida*)	0.094	0.018	111
Wallaby grass (*Danthonia* sp.)	0.190	0.036	56
Snow grass (*Poa* sp.)	0.089	0.018	111
Pinus radiata	0.079		51
Pinus halepensis	0.071		56
Eucalyptus radiata		0.015	133
Eucalyptus maculosa		0.025	80
Wiregrass (*Aristida stricta*) USA		0.007	286
Cheatgrass (*Bromus tectorum*) USA		0.011	189
Twigs (cylinders)		0.1	40
Twigs (cylinders)		0.5	8
Twigs (cylinders)		1.0	4
Twigs (cylinders)		2.0	2

Source: Luke & McArthur, 1978 and Chandler *et al*., 1983.

Figure 4: Barley stubble (left) has a higher surface area-to-volume ratio than canola (right) and hence would burn more readily.

Fuelbed continuity

Fuelbed continuity (vertical and horizontal) is another important property of fuels which affects fire spread rates. Wind speed and moisture content of fuels combine to determine the likelihood of a fire spreading in discontinuous fuels (Catchpole, 2002). Fuel moisture is not likely to be a limiting factor in the peak fire season, however.

Burrows *et al*. (1991) found a wind speed threshold of 10 to 18 km/h to sustain fire spread in hummock grasslands in semi-arid environments and Griffin and Allan (1984) found a threshold of 4 km/h in similar vegetation types, but with a higher level of continuity. Cheney & Sullivan (1997) found the wind speed threshold in temperate and tropical grasslands to be about 5 km/h. This threshold wind speed is a function of the size of the fuel patches versus the size of the gaps between them and the environmental conditions (wind and dryness) (Sandell *et al*. 2006). Burrows *et al*. (1991) noted that the size of the fire front relative to the size of the gaps in the fuel was important to the sustained spread of the fire. In large fires, smaller gaps become less important than for small fires.

Discontinuous fuel affects a range of properties, especially those that affect intensity and flame height. Wind reduces the effect of fuel discontinuity by pushing flames over, creating a higher angle and an increased chance of heating the next fuel element (Beer, 1993, 1995). More intense, higher flames also assist in bridging discontinuities. Where fuel loads are low or discontinuities are large, fires may self-extinguish (Weber, 1990). Fires in poorly continuous fuel are likely to have reduced lateral and backwards spread, and so will have a narrower front and lower flame height (Morvan, 2007), and will be more easily suppressed. However, a wind shift or change in wind direction may suddenly widen the fire and increase its spread rate (Cheney & Sullivan, 1997).

Therefore, one might expect that the threshold wind speed or fire size to get a fire to spread through canola or lupin stubble will be greater than that in cereal stubble in a similar season. In addition, the lateral spread of a fire is likely to be less in more open stubble such as canola because the effective wind speed perpendicular to the prevailing wind direction will be close to zero. Therefore fires in open stubbles will tend to stay narrower for longer than in denser stubbles.

Fuel height

Fuel height is recognised to have a significant effect on fire behaviour when fuel load remained constant. Mowing experiments (Cheney *et al*., 1993, 1998) and field experiments (Savadogo *et al*., 2007) showed that crops or grasses in their natural state had greater rates of spread, flame height and intensity than areas which had been cut or grazed. The CSIRO Grassland Fire Spread Meter includes fuel categories of "eaten out", "grazed" or "natural" state (Cheney & Sullivan, 1997).

The category 'eaten out' can be considered to be equivalent to a harvested crop where residues have been cut and removed or ploughed under. Fuel continuity is limited and loads are low. The category 'grazed', which also includes mown grass (Cheney *et al*., 1993), is similar to harvested crops where stubble is retained. The category 'natural state' is equivalent to crops pre-harvest where fuel heights are maximal. Fires in 'grazed' grass fuels spread at 84% of the rate of grass in the 'natural state'.

Increased fuel height increases intensity and flame height and may also affect the effectiveness of firebreaks. Management can influence fuel height, primarily through the differences between crops but also via harvesting methods. While all crops can be direct-headed with a combine harvester, windrowing prior to harvest is a common practice for canola, barley, lupins and faba beans on Lower Eyre Peninsula. Windrowing reduces the continuity of the fuel load between cutting and harvest, so has the potential to reduce fire risk prior to harvest (Figure 5). Windrowed crops are often cut lower to the ground than direct-headed crops, leaving a shorter stubble following harvest. Both techniques will leave similar amounts of crop residue after harvest, but a lower cut height from windrowing may reduce fire risk.

Figure 5: Windrowed lupin crop on Lower Eyre Peninsula. Fire risk is reduced by the break in continuity of the fuel and the shortened height.

Fuelbed bulk density

Fuel bulk density is the mass per unit volume of the fuelbed. Increasing density by rolling, chaining, raking or mowing crop stubble reduces aeration and decreases flame height without greatly affecting spread rates (Cheney *et al*., 1993). Smouldering time increases with increased fuel compaction. As the same amount of fuel is generally available, residence time increases, but wildfires are both easier to attack directly and less likely to cross firebreaks.

Fuel load

Fuel load is the total amount of available crop or crop residue on site available to be burnt. There has been a considerable amount of research into the importance of absolute fuel load, with load incorporated into some spread models (Scott & Burgan, 2005; Sneeuwjagt & Frandsen, 1977), but not into others (Cheney *et al*., 1993). This is because fuel load is confounded with fuel height, continuity and surface area-to-volume ratio (Luke & McArthur, 1978). Fuel load may have some effect on rate of spread, but this is minimal in comparison to the effects of fuel moisture or wind speed (Cheney *et al*., 1993). However, fuel load does affect residence time and the total amount of heat generated by the fire and therefore contributes to difficulties in the direct suppression of fire and the potential impact of the fire on the environment and structures in its path.

Fuel load varies greatly between crops and seasons, and management practices. Poor seasons could generate as little as 2 t/ha of fuel, whereas a sorghum crop grown under ideal conditions may produce up to 15 t/ha. Table 4 gives estimates of the range of total crop and grain yields, and residual stubble levels likely to be found on Lower Eyre Peninsula. For cereals, pre-harvest yields range from around 3 up to 7.5 t/ha. with post-harvest stubble yields of about 2 to 4 t/ha. Canola and lupins generally produce significantly lower yields, of the order of 50% to 80% of cereals under the same conditions. Note that these are district average values – individual paddocks will show greater yield variability.

Table 4: Crop dry matter, grain yield and post harvest residues for Lower Eyre Peninsula.

CROP	Minimum yield (t/ha)	Median yield (t/ha)	Maximum yield (t/ha)
Total dry matter yield (pre-harvest) [1]			
Wheat	4.0	5.8	7.5
Barley	3.3	5.4	7.5
Canola	1.5	3.3	5.0
Lupins	2.0	3.9	6.0
Grain yield [1]			
Wheat	1.6	2.5	3.4
Barley	1.3	2.3	3.4
Canola	0.6	1.3	2.0
Lupins	0.8	1.6	2.4
Stubble residue [2]			
Wheat	2.4	3.3	4.1
Barley	2.0	3.1	4.1
Canola	0.9	2.0	3.0
Lupins	1.2	2.3	3.6
Grazed pasture (January) [3]	***1.0***	***1.5***	***3.0***

Source: [1] (Primary Industries and Resources SA, 2007).
[2] Stubble residue estimates post-harvest calculated from grain yields, on the basis of:
Cereal stubble dry matter (t/ha) = 1.5 x grain yield at low yields and 1.2 x grain yield at high yields. Median stubble yield calculated as 1.35 x median grain yield.
Canola and lupin stubble dry matter (t/ha) = 1.5 x grain yield.
[3] Grazed pasture residues estimated for early January based on discussions with Rural Solutions SA consultants.

Figure 6 shows the research harvest of barley averaging 4.2 t grain/ha. The fuel levels indicated in the image are likely to support wildfire under a range of conditions, and suppression is likely to be difficult under Extreme fire conditions.

Figure 6: Harvest of barley research plots yielding 4.2 t/ha on Lower Eyre Peninsula.

Seasonal variability can also affect agricultural production, productivity and the selection of crops for planting (Hanks & Puckridge, 1980). Exceptionally dry seasons will enhance forest fire danger (O'Bryan, 2005), but will result in reduced crop yields as well as an increase in the demand and value of residues for stock feed. Figure 7 shows a comparison of canola residues in autumn between high and low yielding paddocks.

Figure 7: Canola stubbles on Lower Eyre Peninsula. Fuel continuity is greatly reduced where a crop yielded 0.8 t/ha (left) compared with a yield of 2 t/ha (right).

It is likely that fire danger in crops and stubbles will be greatest in hot summers that follow a wet spring (Parrot & Donald, 1970).

Fuel calorific values

Fuel energy values have the potential to affect the way fires behave, increasing flame heights and intensity. Typical energy values of stubbles from crops grown on Eyre Peninsula are shown in Table 5.

Table 5: Energy values of crop residues on Eyre Peninsula.

Species	Energy (kJ/kg)
Wheat	18,252
Barley	18,780
Canola	21,604
Lupin	15,719

Source: (ECN, 2008)

The intensity of a fire is commonly reported as the fireline intensity which is calculated with the formula:

$$I = H \cdot w \cdot r$$

where “I” is the fireline intensity (kW/m), “H” is the calorific value of the fuel (kJ/kg), “w” is the amount of fuel actually burnt (kg/m^2) and “r” is the rate of spread of the fire (m/s) (Byram, 1959). So the intensity of a fire is directly proportional to its rate of spread, the amount of fuel burnt and the calorific value of the fuel.

As canola is grown specifically for oil production, the higher oil levels in both pre-harvest canola crops and post-harvest residues, compared with cereal and legume crops, have the potential to affect fire behaviour, particularly in relation to flame height and intensity. This has not been assessed experimentally, however.

Landscape-scale continuity

The spatial continuity of fuel at a landscape level can have important effects on the passage and susceptibility of a landscape to wildfire. Increased cropping intensity on Lower Eyre Peninsula, resulting in a more continuous fuel pattern, is probably the major contributor to enhanced fire risk in recent years. Where a mix of crop species and varieties is used, fire behaviour will change as a wildfire moves from one fuel type to another. Influences such as moisture differentials between crops or grazed pastures can be important in controlling wildfire for use as breaks or anchor points for suppression activities. Temporal variation in crop maturity and variability in harvest dates can contribute to landscape heterogeneity. Continuous or more intensive cropping may reduce spatial variation in the landscape, resulting in a more homogenous grass fuel rather than a mosaic of highly flammable and poorly flammable areas. A homogenous landscape provides fewer safe areas from which to mount fire suppression efforts.

4.0 Impediments to fire spread

The majority of the area (~85%) that was burnt in the Wangary fire of 2005 consisted of grassland fuel types including pastures and crop stubbles (Schapel, 2007). The Fire Danger Rating was Extreme at times during the progression of the fire, with the Grassland Fire Danger Index (GFDI) reaching levels of over 50 for a number of hours on both January 10th and 11th. Under these conditions the headfire travelled at rapid rates and there was no potential for successful suppression except in the early stages of the fire development. Once the GFDI reduced due to changing weather conditions, the fire became more manageable and could be controlled with the use of natural and manmade breaks in fuel. Under Extreme fire conditions, the spread of the Wangary fire in grass fuel types was unhindered by a range of fuel barriers, including roads, creeks and swampy areas with live vegetation. This type of progression is not unique to the Wangary fire; there is a number of precedents for grassfires that burn in this manner in south-eastern Australia. The fires in the western districts of Victoria in 1977 (Cheney, Barber, & McArthur, 1982) and fires in the Otway Ranges in Victoria 1982/83, (Billing, 1983) and in central Victoria in 1986 (Billing, 1987) all exhibit similar patterns. These fires had very high rates of spread under Extreme fire danger conditions, and were able to cross numerous barriers where fuel was absent or low quality.

The firebreak system in the western Victorian fires did not stop the spread of the fire under Extreme conditions. However fire progression was influenced by some aspects of fuel even under these Extreme conditions. Large areas of low fuels prevented or slowed fire progression, and the effectiveness of barriers was proportional to their size. Table 6 gives an indication of the scale of barriers that were able to significantly influence fire spread under Extreme fire conditions. All these fires crossed a range of barriers such as roads and creeklines that would have stopped less intense fires.

Table 6: Barriers that influenced fire behaviour under Extreme conditions in initial fire run at some historic grassfires.

Fire	Date	Factors significantly influencing headfire behaviour	Barrier size (m)
Heathcote - Bendigo fire 38[1]	16/01/1987	Fuel moisture differential (creekline)	30-100
Byaduk North Fire[2]	12/02/1977	Fuel moisture differential (swamp)	~500
Strathmore / Glenthompson fire[2]	12/02/1977	Fuel absent (lake)	1000
		Low fuels (heavily grazed pastures)	~500
Pura Pura - Derrinallum Fire[2]	12/02/1977	Low fuels (clover)	~500
Little River Fire[2]	12/02/1977	Low fuels (road)	30
Tatyoon-Streatham Fire[2]	12/02/1977	Low fuel and moisture differential (swamp)	1000
Wangary Fire[3]	10/1/2005	Moisture differential and poor fuels (swamp)	~250

Sources: 1: (Billing, 1987)
2: (Cheney *et al*., 1982)
3: (Gould, 2005)

A narrow firebreak can be effective for low intensity fires or fires in the early stages of development, whereas even a very large firebreak may not be effective in halting a well established fire under Extreme conditions. Firebreaks are most effective at stopping low intensity fires spreading by radiant and convective means (Morvan, 2007). Where there are airborne firebrands from burning trees or shrubs, their effectiveness is reduced (Davidson, 1988; Wilson, 1988). This is also the case where grass species have large or loose seed heads that can be carried by wind across the firebreak (O'Bryan, 2005). Firebreaks are most effective when the fire does not approach perpendicular to the break. The optimal width of the firebreak is dependent on the expected flame height of the fire, with a break expected to be effective if it is greater than 1.5 times the flame height. Under Extreme conditions, even when firebreaks are present, the required break size with a mature crop may not be feasible, and standard breaks may not be adequate (Fogarty & Alexander, 1999).

Figure 8 provides an indication of the progression of the Tatyoon-Streatham fire in 1977 and its obstruction due to swampy land and roads. The example fires listed in Table 6 are similar to the Wangary fire in that they were burning through mixed fuel types, so that burning embers from woody vegetation may have been partially responsible for the ease with which the fires crossed roads and other breaks in fuel.

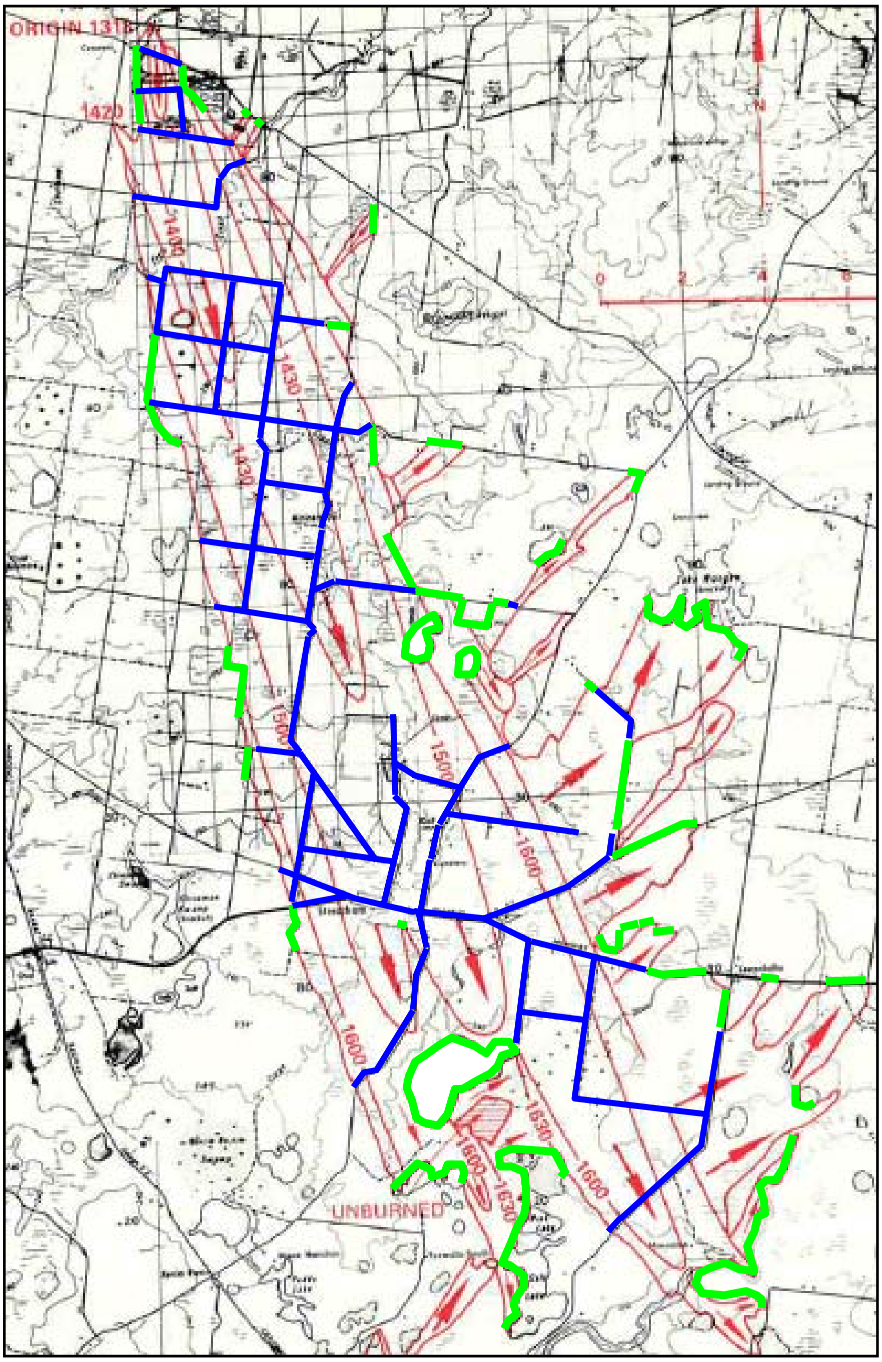

Figure 8: The progression of the Tatyoon-Streatham fire in the western districts of Victoria, 1977. Red lines indicate fire progression (isochrones) (Cheney *et al*., 1982). Blue lines indicate potential firebreaks breached by the fire and green lines indicate firebreaks effective in halting the spread of the fire.

5.0 Farming systems on Lower Eyre Peninsula

The Eyre Peninsula is an important cropping region, producing around 45% of South Australia's wheat crop and 20% of its annual barley production (Martin *et al.*, 2006). The area has a gross annual value of agricultural production of over $500 million, most of which is derived from broadacre farming. Wheat is the dominant crop grown, followed by barley. Other crops grown in the area include canola, lupins and other pulse crops (field peas and faba beans). Meat and wool production from sheep and lambs are also major income earners for the region. Figure 9 indicates the value of agricultural commodities from the Eyre Peninsula as a whole. Lower Eyre Peninsula takes in the higher rainfall southern region of Eyre Peninsula, and accounts for approximately 40% of the region's agricultural production.

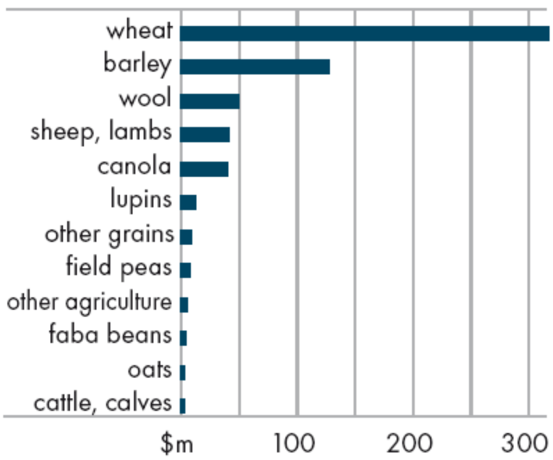

Figure 9: Commodity values in the Eyre Peninsula for 2003/04. Source: (Martin *et al*., 2006).

5.1 Changing farming practices on Lower Eyre Peninsula

The Lower Eyre Peninsula has traditionally been farmed using rotational "ley farming" methods, which rotate cereal crops with legume and grass pastures. In more recent years, the development of sustainable farming practices has provided for the intensification of cropping, allowing cropping to occur in a continuous cycle with minimal degradation of soil properties (Chan & Heenan, 1996). Cropping is currently limited to winter crops, i.e. wheat, barley, canola and pulses (grain legumes), although the potential for warm season crops such as sunflowers or sorghum has been investigated (Growden and Wilhelm, 2004). Warm season crops rely on summer rainfall, and as the Eyre Peninsula has a winter-dominant rainfall pattern (i.e. "Mediterranean-type" climate), winter crops will continue to dominate agricultural production. More intensive cropping systems involve rotation of crops, with cereals the primary crop type, pulses used to increase soil nitrogen and canola used as a break-crop to restrict the build-up of soil-borne cereal diseases (Adcock, 2005).

The practices used in more intensive cropping and conservation tillage systems on Lower Eyre Peninsula include minimum tillage, direct drill sowing and stubble retention. These techniques are intended to minimise nutrient loss and evaporation from the soil by maintaining soil structure and / or cover of vegetation over the site (Chan & Heenan, 1996). This has the potential to increase crop yields while maintaining soil properties. Features of key conservation farming practices are described in Table 7.

Table 7: Conservation farming practices used on Lower Eyre Peninsula.

Practice	Description
Direct drilling	A cultivation technique where no pre-sowing tillage is required. When planting, seeds are drilled directly into the soil, often with more narrow sowing tynes. The soil surface is maintained relatively intact and residues from previous crops are most often retained, although some may be removed by harrowing (raking) or a "cool" burn, to minimise problems with stubble blockages around the sowing tynes.
Minimum tillage	A cultivation technique where areas are tilled to the minimum depth required for the germination of the subsequent crop, but there is no inversion of soil, so the majority of crop residues remain at the surface. Minimum tillage also involves fewer cultivation passes, again reducing the burial and breakdown of crop residues. Strip tillage could be considered to be a form of minimum tillage where narrow strips are tilled for crop planting, but the majority of the soil is undisturbed and residues remain at the surface.
Row spacing	Wider row spacing on sowing implements reduces soil disturbance and leaves more stubble intact on the soil surface.
Stubble retention	Stubble retention is where harvest residues are retained on site after harvest, and subsequent crops are planted into the residue. Residues may be raked (harrowed), chained, slashed or rolled as part of preparation for sowing. Occasionally a "cool burn" may be employed in late autumn to reduce the bulk of dry residue and destroy weed seeds and/or snails.

Conservation tillage techniques are in contrast to traditional tillage practices where soil is ploughed more deeply and with wider shares, resulting in greater soil disturbance and burial of crop residues as the soil is inverted. Stubble may be harvested for sale as straw, grazed or now more rarely burnt. Traditional agricultural practices incorporate a pasture phase where soils are rested between crops. Livestock (sheep and cattle) graze on pasture areas and also feed on crop residues after harvest. A consequence of the shift to more frequent cropping is the reduction in pasture area for maintaining livestock, and hence a reduced number of livestock on farms in the region. As livestock numbers in the region decrease, the potential for managing levels of crop residues through grazing is reduced. The trend to increased cropping intensity in recent years has been driven in part by higher returns and profitability of cropping compared with livestock enterprises (sheep for wool and meat and cattle for meat). Paddock survey data collected in a transect across Lower Eyre Peninsula each October in the Department of Water, Land and Biodiversity Conservation's Land Conditioning Monitoring Program indicate that the approximate proportion of paddocks in crop each year ranged from 67% to 83% over the 5 year period to 2007 (G. Forward, *pers. comm*.).

A variety of cropping techniques is used across the Eyre Peninsula (Figure 10), and the use of conservation tillage practices to sustain more intensive cropping could be expected to increase as benefits are more widely recognised (Adcock, 2005).

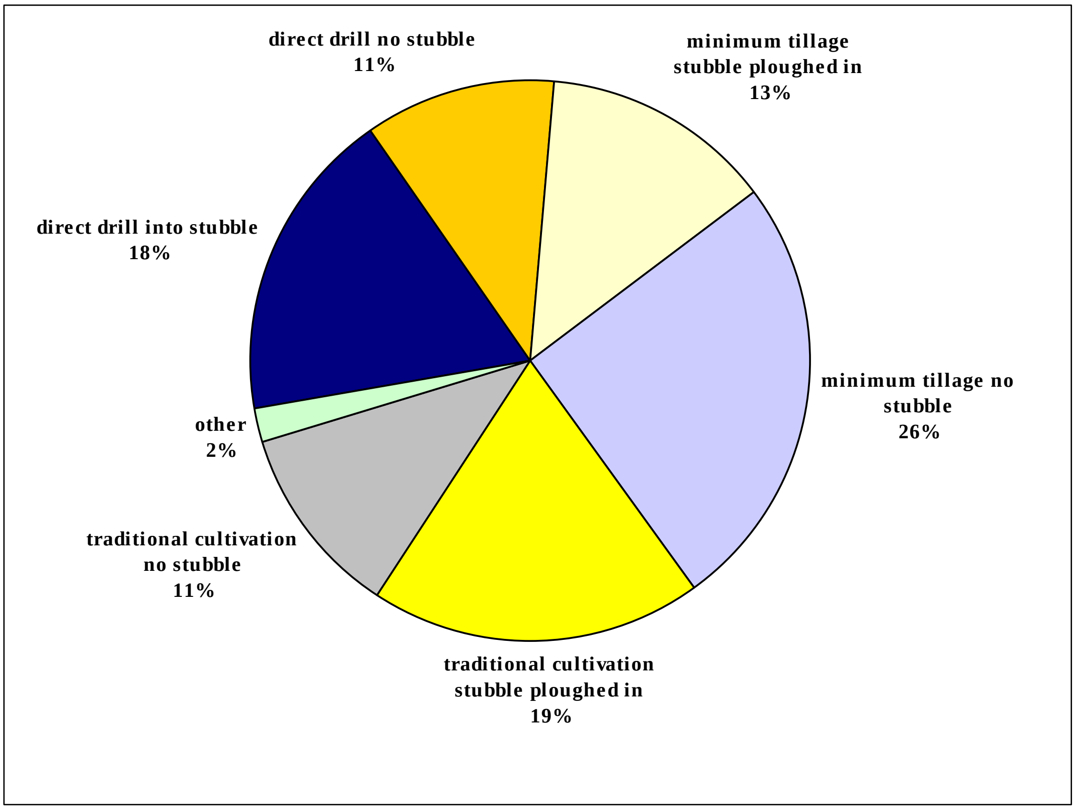

Figure 10: Cultivation practices used on the Eyre Peninsula, 2001/02. **Source: (ABARE, 2002).**

In 2001/02, a total of 31% of crops had stubble retained after harvest, with 18% of those with stubble using direct drill sowing and 13% utilising minimum tillage practices. The remaining 69% either had stubble removed, grazed, or ploughed in with traditional cultivation (ABARE, 2002). Grazing reduces both the mass and height of stubble, and prevents significant weed growth. Cultivation may occur after harvest or paddocks may be cultivated before the autumn break as a weed management method. Under conservation tillage methods, post-harvest weeds are controlled with herbicide if necessary. A consequence of stubble retention is that potential fuel for wildfire is maintained on site after harvest, increasing the continuity of the landscape to fire.

5.2 Implications of farming trends on potential fire behaviour

The main implication of recent farming trends on the Lower Eyre Peninsula is a greater continuity of fuels across the landscape and hence the potential for more extensive fires. The use of conservation tillage practices, including minimum tillage, direct drilling and stubble retention has led to higher productivity and more sustainable farming systems, but these practices are not likely to have directly altered the fire threat significantly.

Major changes associated with increased use of conservation farming practices include more frequent cropping, reduced livestock grazing, and reduced cultivation and burning of stubbles. There has also been an increased reliance on herbicides for summer weed control, in lieu of cultivation. The net result of these changes, in terms of fire risk, is that over-summer fuel loads across the region have increased, with less grazed pastures and more standing crop stubble remaining in paddocks.

More intensive cropping and reduced levels of grazing mean that there are fewer pasture areas interspersed across the landscape and less removal of plant biomass, both pasture and crop stubble, by grazing animals. In dry years, pastures are likely to be heavily grazed, providing areas of low fuels interspersed through the cropland. The standing fuel biomass over the fire season is therefore greater where grazing is reduced.

Reduced grazing is also resulting in the lesser need for fences. Some fences are being removed across the landscape to improve the ease of cropping, but this will also provide some benefit to firefighting by improving access to fires.

Low levels of grazing and increased levels of cropping have resulted in greater areas of stubble. The availability of this stubble may provide new market opportunities for straw harvesting and sales. This may compensate somewhat for the reduced grazing impact, with the potential to break up and reduce the fuel hazards across the landscape.

Cultivated or mown fire breaks around the perimeter of paddocks and farms are now much less common. Provided they are properly maintained, such fire breaks can reduce the risk of fires starting and facilitate early fire control. However, the evidence is that they are ineffective against major fires of the scale and conditions of the 2005 Wangary fire.

The aim of stubble retention techniques is to retain higher levels of crop residue on or near the soil surface, for multiple benefits of soil protection, moisture conservation, nutrient cycling and improved soil structure and biology. Although hard data are lacking, an estimate of the rate of "disappearance" of surface crop residues under a continuous crop regime is that only 30% will remain after 12 months (Jeff Baldock, CSIRO Land and Water, *pers. comm*.). Thus in a continuously cropped paddock with stubble retention (including no grazing), the fuel load is likely to reach an equilibrium or plateau level of around 40% higher than one year's stubble or residue after four years of cropping. The bulk of the older residue will also be flat on the soil surface after a subsequent crop year, and thus present a lower fire risk.

The adoption of conservation farming techniques on Lower Eyre Peninsula is likely to continue. However, the potential for further intensification of cropping above the current level of 75-80% is limited, as many farmers now recognise that some soil types are better suited to pasture production than cropping, and that there are advantages in retaining livestock in their farming systems. These decisions are very dependent on comparative financial returns from grain and livestock, however.

6.0 Potential fire mitigation options on the Eyre Peninsula

Firebreaks can play an important role in managing fire risk and protection of crops. Firebreaks of 500 to 1000 metre are needed in grazing / cropland to significantly alter or halt the spread of a major wildfire under Extreme conditions. However, much smaller firebreaks are effective at stopping fire spread on the flanks of the fire, when the fire is less well developed or when weather conditions are more moderate. Such firebreaks can also be used as lines for backburning and as anchor points for suppression activities. Firebreaks provide additional benefits including safe access for firefighters and protection for fence lines.

Several issues that need to be addressed for the implementation of firebreaks as an effective management strategy are:

- Optimisation and education about firebreaks, including the management of woody vegetation, and optimisation of break direction in relation to prevailing winds.
- Establishment of a legal framework to ensure firebreaks are present and meet minimum standards. Firebreaks are recommended, but are not currently mandatory (CFS, 2008a).

A number of other strategies can also be considered to reduce the potential for large scale landscape fires. Some potential strategies are listed below, but this list is by no means exhaustive.

- Strategic planning for fire control, such as establishment of farm cooperatives to plan fire management at a landscape scale. This could include a strategic pattern of cropped, cultivated and grazed paddocks to provide firebreaks and safe refuges for livestock in the event of fire, and protect buildings and facilities.
- Consider landscape spatial conformation of crops, with the aim of reducing continuity of large areas of fuel. Selection of crop type may have some influence on fire behaviour due to changes in structure, rate and degree of curing, height and energy value, but under Extreme weather conditions the influence of fuel will be less important (Noble, 1991).
- Optimisation of harvesting practices, including harvesting crops as soon as moisture levels allow and closer to the ground to reduce stubble height. Straw spreaders can be used at harvest to chop harvested straw to further reduce height and ensure greater fuel bulk density. Increased use of windrowing in suitable crops may also reduce fire risk, both before and after harvest, with lower stubble heights and greater opportunity for fuel compaction.
- Strategic management of retained stubble to reduce potential flame heights, such as grazing, rolling, chaining, harrowing or slashing.
- Mowing, baling and removal of crop residues for alternative uses such as the sale for feedstock or use as a cellulose source. Industry development to improve markets for residues could be considered.
- Increased community education about fire safety and planning guidelines.
- Where it is recognised that there is a trend to conditions which are more likely to support large fires, investment in early detection and communication combined with rapid first attack technology such as aircraft.

7.0 Conclusions

This review has highlighted that while grassfires have been the focus of a reasonable amount of research, there have been no specific studies focusing on wildfires in crops and crop residues under different management practices.

It is expected that there will be a significant difference in the fire behaviour in cereal crops and stubbles compared with canola and pulse crops and stubbles, due to their different stalk dimensions and spatial density.

On the balance of the evidence presented in this review, the greatest change to fire risk with the trend to more frequent cropping and less grazing is the greater continuity of fuels across the landscape and hence the greater potential for fire to become large and more severe. The use of minimum tillage practices does not, on their own, change the fire risk significantly.

Where crop residues are grazed, harvested or ploughed in, fire intensity and spread rates are likely to be reduced.

Firebreaks of 500 to 1000 m are needed in grazing / cropland to significantly alter or halt the spread of a major wildfire under Extreme conditions. However, much smaller firebreaks are effective at stopping fire spread on the flanks of the fire, when the fire is less well developed or when weather conditions are more moderate.

Spatially explicit consideration of cropping and land management practices may allow some amelioration of increased fire risks, but further research is needed to highlight vulnerabilities and assist with strategy development.

This review has identified significant knowledge gaps in the management and risks posed by current farming practices. In order to make informed decisions in managing fires at a landscape level on Lower Eyre Peninsula, potential research topics include:

- The effects of seasonality, crop species and yield on fire behaviour under various scenarios;
- Characterization of different crop types in terms of their fuel surface-to-volume ratios, fuel gap size, and degree of continuity and fuel loads;
- Seasonal and annual trends in fuel properties in the Lower Eyre Peninsula in relation to fire weather;
- Potential uses and markets for cropping residues including grazing and baled straw;
- Strategic landscape management, including optimisation of paddock sizes, firebreaks, crop layouts, species mixes, grazing levels;
- The effects of conservation farming practices on fuel properties including fuel retention, breakdown and soil mulches;
- Future requirements for fire detection, management and suppression based on expected trends.

8.0 References

ABARE. (2002). Research Management Survey Data Package, 2001/02 (Publication. Retrieved 10/4/2008, from Australian Bureau of Agriculture Resource Economics: http://www.abareconomics.com/ame/lrm2/lrmalt.asp

Adcock, D.P. (2005). *Soil, water and nitrogen dynamics of farming systems on the upper Eyre Peninsula, South Australia.* The University of Adelaide, Adelaide.

Anderson, H.E. (1982). *Aids for determining fuel models for estimating fire behaviour*. Ogden: Intermountain Forest and Range Experiment Station.

Baxter, G.J., and Woodward, S. R. (1999). *Estimating grassland curing using soil moisture indicators and a pasture quality model.* Paper presented at the Australian Bushfire Conference, Albury.

Beer, T. (1993). The Speed of a Fire Front and Its Dependence on Wind-Speed. *International Journal of Wildland Fire, 3*(4), 193-202.

Beer, T. (1995). Fire Propagation in Vertical Stick Arrays - the Effects of Wind. *International Journal of Wildland Fire*, *5*(1), 43-49.

Billing, P. (1983). *Otways fire no 22 - 1982/83: Aspects of fire behaviour* (No. 20).

Billing, P. (1987). *Heathcote fire; Bendigo fire 38 1986-87* (No. 27).

Burrows, N.D., Ward, B. and Robinson, A. (1991). Fire behaviour in spinifex fuels on the Gibson Desert Nature Reserve, Western Australia. *Journal of Arid Environments* **20**, 189-204.

Byram, G.M. (1959). Combustion of forest fuels. **In:** K.P. Davis (ed.), "*Forest Fire Control and Use*", McGraw Hill, New York.

Catchpole, W. (2002) Fire properties and burn patterns in heterogeneous landscapes. **In**: R.A. Bradstock, J.E. Williams and A.M. Gill (eds.), *Flammable Australia – The Fire Regimes and Biodiversity of a Continent.* Cambridge University Press. Pp. 45-75.

CFA. (1999). *Grassland curing guide*: Country Fire Authority.

Country Fire Service, South Australia (2008a). Draft Grain Harvesting Code of Practice, retrieved from: http://www.cfs.org.au/grainharvesting/GHCOP_GFDI_index_table.pdf

Country Fire Service, South Australia (2008b). Draft Grain Harvesting Code of Practice – Explanatory Notes, retrieved from: http://www.cfs.org.au/grainharvesting/GHCOP_brochure.pdf

Chan, K.Y., and Heenan, D.P. (1996). Effect of tillage and stubble management on soil water storage, crop growth and yield in a wheat-lupin rotation in southern NSW. *Australian Journal of Agricultural Research, 47*(3), 479-488.

Chandler, C.P., Cheney, N.P., Thomas, L., Trabaud, L., and Williams, D. (1983). *Fire in Forestry. Vol. I: Forest Fire Behaviour and Effects*. John Wiley and Sons, New York, 450 pp.

Cheney, N.P., Barber, J., and McArthur, A.G. (1982). *The fires of 12 February 1977 in the western district of Victoria*. Melbourne: CSIRO.

Cheney, N.P., and Gould, J.S. (1995). Fire Growth in Grassland Fuels. *International Journal of Wildland Fire, 5*(4), 237-247.

Cheney, N.P., Gould, J.S., and Catchpole, W.R. (1993). The influence of fuel, weather and fire shape variables on fire-spread in grasslands. . *International Journal of Wildland Fire, 3*(1), 31-44.

Cheney, N.P., Gould, J.S., and Catchpole, W.R. (1998). Prediction of Fire Spread in Grasslands. *International Journal of Wildland Fire, 8*(1), 1-13.

Cheney, N.P., and Sullivan, A. (1997). *Grassfires: Fuel, Weather and Fire Behaviour*. Collingwood, Australia: CSIRO Publishing.

Clements, C.B., Clements, C.B., Shiyuan, Z., Goodrick, S., Ju, L., Potter, B.E., *et al*. (2007). Observing the dynamics of wildland grass fires: FireFlux--A Field Validation Experiment. *Bulletin of the American Meteorological Society, 88*(9), 1369.

Davidson, S. (1988). Predicting the effectiveness of firebreaks. *Rural Research, 139*, 11-16.

ECN. (2008). Phyllis; the composition of residues and biomass (Publication from Energy Research Centre for the Netherlands: http://www.ecn.nl/phyllis/single.html

Egan, J.P., Crouch, J.S. and Hawthorne, W.A. (2007). Lupin variety sowing guide 2008. *Grain Business 22*: 62-64. (PIRSA Fact Sheet 18/00/08).

Fernandes, P.M. and Rego, F.C. (1998). A new method to estimate fuel surface area-to-volume ratio using water immersion. *International Journal of Wildland Fire,* **8**(2), 59-66.

Fogarty, L.G., and Alexander, M.E. (1999). *A Field Guide for predicting grassland fire potential: derivation and use* (No. 20). Rotorua: Forest Research.

Gould, J. (2005). Development of bushfire spread of the Wangary fire; 10th and 11th January, 2005. Lower Eyre Peninsula, South Australia. In G. o. S. Australia (Ed.), *Coroners Report Wangary Fire*. Adelaide: South Australia State Coroners Office.

Griffin, G.F. and Allan, G.E. (1984). Fire behaviour. **In**: E.C. Saxon (ed.), *Anticipating the Inevitable: A Patch Burn Strategy for Fire Management at Uluru (Ayers Rock – Mt Olga) National Park.* CSIRO Melbourne. Pp. 55-58.

Growden, B. and Wilhelm, N.S. (2004). Summer crops for southern Australia – what have we learnt? In Eyre Peninsula Farming Systems 2003 Summary, p 43-44.

Hanks, R.J., and Puckridge, D.W. (1980). Prediction of the influence of water, sowing date and planting density on dry matter production of wheat. *Australian Journal of Agricultural Research, 31*(1), 1-11.

Kemanian, A.R., Stockle, C.O., Huggins, D.R., and Viega, L.M. (2007). A simple method to estimate harvest index in grain crops. *Field Crops Research, 103*(3), 208-216.

Luke, R.H., and McArthur, A.G. (1978). *Bushfires in Australia.* Australian Government Publishing Service.

Martin, P., Van Mellor, T., O'Donnell, V., and Lawrence, L. (2006). *Financial performance of farms in the Eyre Peninsula of South Australia.* Paper presented at the Eyre Peninsula Regional Outlook Conference.

Mell, W., Jenkins, M.A., Gould, J., and Cheney, P. (2007). A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire, 16*(1), 1-22.

Morvan, D. (2007). A numerical study of flame geometry and potential for crown fire initiation for a wildfire propagating through shrub fuel. *International Journal of Wildland Fire, 16*(5), 511-518.

Noble, I.R., Bary, G.A., and Gill, A.M. (1980). McArthur's fire danger meters expressed as equations. *Australian Journal of Ecology, 5,* 201-203.

Noble, J.C. (1991). Behaviour of a very fast grassland wildfire on a riverine plain of South-eastern Australia. *International Journal of Wildland Fire, 1*(3), 189-196.

O'Bryan, D. (2005). *The Science of Bushfire Behaviour* (Vol. 1): Papyrus publishing.

Parrot, R.T. (1964). *The growth, senescence and ignitability of annual pastures.* University of Adelaide, Adelaide.

Parrot, R.T., and Donald, C.M. (1970). Growth and ignitability of annual pastures in a Mediterranean environment. 2. Ignitability of swards of various annual species. *Australian Journal of Experimental Agriculture, 10*(42), 76-83.

Primary Industries and Resources SA (2007). *Field Crop Production Estimates; Monthly Crop and Pasture Reports, 1998 - 2007*.

Rothermel, R. (1972). A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Research Paper INT-115. Intermountain Forest and Range Experimental Station, Ogden, Utah. 40pp.

Sandell, P., Tolhurst, K.G., Dalton, J., Scott, B. and Smith, M. (2006). Fire management prescriptions for the Victorian Mallee Parks. *Proceedings of the Royal Society of Victoria*, **118**(2), 395-412. ISSN: 0035-9211.

Savadogo, P., Zida, D., Sawadogo, L., Tiveau, D., Tigabu, M., and Oden, P.C. (2007). Fuel and fire characteristics in savanna woodland of West Africa in relation to grazing and dominant grass type. *International Journal of Wildland Fire, 16*(5), 531-539.

Scott, J.H., and Burgan, R.E. (2005). *Standard Fire Behavior Fuel Models: A comprehensive set for use with Rothermel's surface fire spread model*: Rocky Mountain Research Station.

Schapel, A.E. (2007). Inquest into the deaths of Star Ellen Borlase and others, Wangary, 11 January 2005. Delivered, 18 December 2007, Anthony E. Schapel, Deputy State Coroner, South Australia.

Sneeuwajagt, R.J., and Frandsen, W.H. (1977). Behavior of experimental fires vs predictions based on Rothermal's fire model. *Canadian Journal of Forest Research, 7,* 357-367.

Weber, R.O. (1990). A model for fire propagation in arrays. *Mathematical and Computer Modelling, 13*(12), 95-102.

Wilson, A.A.G. (1988). Width of firebreak that is necessary to stop grassfires: Some field experiments. *Canadian Journal of Forest Research, 18*, 682-687.