Developments in stubble retention in cropping systems in southern Australia

Report to the GRDC

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Report to GRDC on Project DAN 00170

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Foreword

Welcome to the review 'Developments in stubble retention in cropping systems in southern Australia'.

The Grains Research Development Corporation has commissioned this review as an update of the Graham Centre Monograph No. 1, 'Stubble Retention in Cropping Systems in Southern Australia: Benefits and Challenges'. The aim is to identify the research, development and extension (RD&E) gaps of a current GRDC investment 'Maintaining Profitable Farming Systems with Retained Stubble', that involves a suite of local projects undertaken by grower groups in collaboration with research organisations and agribusiness.

The majority of growers retain stubble opportunistically. This was clear from survey data that showed a low frequency of burning (2–3%) during the Millennium Drought, followed by a spike in burning of 35–40% in the high rainfall zones in 2011. Research suggests that while the environmental benefits of full stubble retention are well understood, many growers find it difficult to effectively integrate multiple components of the stubble retention system when faced with challenging issues, such as those of 2011. Currently there is a lack of compelling evidence that clearly demonstrates the economic benefit of adopting full stubble retention for productivity gains and environmental benefits and further research is required.

The update process has collated, reviewed and analysed existing RD&E material on stubble retention in farming systems in southern Australia. The audit included published literature and 'grey literature', primarily from grower groups, and has enabled the identification of gaps in RD&E. It has also resulted in a valuable compilation of data from the grower groups.

We hope you enjoy this update and we look forward to producing further topical and challenging reviews in the future.

Ms Deb Slinger
Manager Southern Cropping Systems
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SUMMARY

This review updates the 2010 Graham Centre Monograph, *Stubble Retention in Cropping Systems in Southern Australia: Benefits and Challenges* (Scott *et al.* 2010). It expands on research data and extension materials from the past few years for south-eastern Australia, including the results from GRDC funded grower groups. This update also includes some issues not referenced in the original monograph (Scott *et al.* 2010).

Prior to 2010, eight years of dry seasons made moisture conservation a priority for growers and during this period stubble retention was generally well adopted. During the past three years (2010-2012), with above average rainfall and heavier stubble loads, growers have been forced to burn stubble to address management issues including machinery trash flow, crop establishment, herbicide-resistant weeds, and pest and disease problems. Machinery development and stubble handling have become key priorities for growers.

Until the early 2000s the emphasis of conservation farmers had been natural resource management (NRM) and fuel and labour savings, with erosion mitigation and soil protection the main drivers for implementing stubble retention practices. While the NRM initiatives fostered commitment among conservation farming advocates, they have not provided the compelling economic evidence needed to persuade mainstream growers of the need to change from the traditional practice of burning stubbles to full stubble retention. Few research trials conducted in the last decade have conclusively demonstrated the economic benefits of full stubble retention.

Low frequency of stubble burning during the Millennium Drought seasons (2002-2009) indicated a large proportion of growers in the GRDC southern region will opportunistically retain stubble. However, better seasons from 2010 onwards have seen a return to heavier stubble loads and extensive burning of stubbles. Regional surveys and consultation with growers indicate variable capacity and commitment of individuals to manage multiple components of complex stubble retention systems.

The benefits of conservation farming are assumed to accrue through improved soil health with subsequent benefits to crop yield and quality or reduced inputs to the farming enterprise. This may be true, if in a mixed farming system, the ratio of crop to pasture is stable. There is evidence this stability is not the case, and the farming system itself has changed to more cropping years and fewer pasture years. Any advantage of conservation farming may not necessarily be expressed as improved soil health, but as the potential for more cropping.

Heavy stubble loads are frequently encountered within the medium and high rainfall zones of the GRDC southern region. This frequency is the result of high grain yield, but also of high stubble loads, immediately post-harvest, at any given grain yield. For example, trials carried out across Australia show that a 2 t/ha grain crop in Queensland would appear to average about 1.8 t/ha of stubble immediately post-harvest. Reports from Western Australia indicate a stubble estimate of 3.6 t/ha, and at Wagga Wagga NSW 5.7 t/ha of stubble would be expected. The amount of stubble present at sowing is also influenced by the rate of breakdown of stubble between harvest and sowing of the subsequent crop.

Standing stubble effectively reduces wind speed at or near ground level. However, the effect of stubble on soil water storage during fallow is highly variable and depends on timing and amount of rainfall. This variability has recently been modelled and modelling offers the potential to better describe the effects of stubble retention on moisture storage across

different seasons. The 'pulse paradigm' considers pulse size of soil water in relation to the frequency and duration of rainfall and soil moisture movement to depth. Rainfall variability is viewed as different possible sequences of rainfall events that create pulses of water into the soil, which are then lost to evaporation from the surface. For a single rainfall event retained stubble will only delay the evaporative loss of the infiltrated water. Cumulative evaporation from the system with residue will catch up to that without residue if it is not followed by a second 'pulse'. This means the benefits of retained stubble are determined by the soil water pulse size and duration, frequency and timing and the evaporative demand. If a second pulse occurs before full drying of the first pulse, water can move further down the soil profile in the delayed system (with residue). This becomes ‘stored’ soil water if it is pushed beyond the evaporation zone of the soil profile.

It is reasonable to assume that retained stubbles will eventually return the nutrients they contain back into the farming system. However, many claims of loss of nutrients from stubble burning are probably exaggerated. At Wagga Wagga, NSW after 21 years of a wheat-lupin rotation in a no-till system where stubble was either burnt or retained, the annual rate of change (loss) of total soil nitrogen was -13 kg/ha/year for retained stubble and -28 kg/ha/year for burnt stubble. The difference (15 kg/ha/year) is the result of retaining stubble compared with burning stubble. Any advantage of retained total nitrogen would not all be available to the plant, but can be seen as a long-term benefit in retained stubble systems in conserving rather than accumulating nitrogen.

Burning stubble produces smoke and contributes to particulates in the air that are a potential cause of health problems. Frequent high particulates in autumn at Wagga Wagga, NSW and to a lesser extent Albury, NSW were attributed to stubble burning. The high frequency of particulate exceeding standards at Wagga Wagga in 2002–2009 was probably due to dust resulting from dry conditions. The exceedances in autumn were probably a result of this being the time of the year with minimal groundcover. However, the contribution of stubble burning to particulate levels in the air remains undefined, but is recognised as probably less important than previously thought.

The ability of retained stubble to increase soil organic carbon (SOC) levels has generally been slow to negligible in Australian no-till cropping systems. As an example, at Wagga Wagga SOC declined over 26 years by 52 kg/ha/year when stubble was retained, and was lost at 98 kg/ha/year where stubble was burnt. These loss rates were not statistically different from one another and not different from zero. Recent scientific reviews on the subject in Victoria conclude there is presently limited potential for carbon accumulation in soils either there, or more generally in Australian agricultural soils. Suggestions as to why SOC is not accumulating under no-till stubble retained systems include inadequate stubble loads (i.e. low carbon input) and/or that other nutrients essential to sequester carbon are limiting.

The adoption of no-till systems using disc seeders (zero-till) is currently increasing in continuous cropping systems as it enables minimal soil disturbance and retention of greater amounts of stubble, particularly at narrow row spacings. Widening of row spacing is primarily a machinery modification to assist the passage of sowing equipment through heavy stubble loads. At higher potential grain yields of wheat and wider row spacings it is clear the yield losses can be substantial - at 4 t/ha in 18 cm rows doubling row spacing to 36 cm reduces yield by 9.5%. Canola yields of 2.5 t/ha at 18 cm row spacing are reduced by 7% by doubling row spacing to 36 cm.

The adoption of inter-row sowing is another innovation aimed at handling heavy stubbles. Growers using inter-row sowing have commonly adopted row spacings of between 22.5 and 30 cm, with installation of 2 cm guidance systems enabling accuracy for row placement. Inter-row sowing enables machinery to avoid stubble for ease of sowing and herbicide application. It also has advantages in slowing crown rot infection of emerging seedlings in wheat-on-wheat sowings. Herbicide carry over effects in inter-row cropping can limit the choice of the second crop after the application of some herbicides to the first crop.

Grazing stubble has associated benefits including reducing high stubble biomass before sowing, utilisation of residual grain and consumption of green summer plants. But there are potential disadvantages of grazing stubble including hoof damage to soil structure and reduced water infiltration rates. However, there is relatively little (<10%) or no effect on subsequent crop growth and yield if excessive grazing is avoided. The risks can be minimised by avoiding overgrazing to maintain groundcover and avoiding excessive grazing in wet conditions. In southern NSW, soil nitrogen levels have been shown to be higher, and wheat yield and protein were the same or higher, following grazing by sheep. This finding was attributed to more rapid nitrogen cycling in grazed systems.

Stubble may carry over for more than one year, adding to the amount of stubble to be sown through. Carryover stubble also can be a source of disease, not only in the first crop sown into retained stubble, but also for a second crop.

Of the wheat diseases carried over on stubble, yellow leaf spot (YLS) was frequently reported as misdiagnosed in the NSW and Victoria. Symptoms were confused with nitrogen deficiency, herbicide phytotoxicity, frosts and aluminium toxicity. These misdiagnoses can lead to unnecessary fungicide treatments.

Crown rot is an important disease of wheat in the GRDC northern region and appears to be of increasing importance in the GRDC southern region. A survey of 76 paddocks in southern NSW during 2012 revealed crown rot to be ubiquitous.

Complete control of rhizoctonia has been reported at Avon, South Australia, 5-10 years after adoption of full stubble retention, in systems with limited grazing and high nutrient inputs. Disease suppressive soil activity was considered a function of microbial populations, composition and activity. However, the SA experience must be kept in geographical context as there is no evidence for suppressive soil activity in other areas of the GRDC southern region.

The GRDC southern region provided abundant evidence of pest-related issues associated, at least in part, with stubble retention. Changes in farm management practices and varying climatic patterns are contributing to a shifting complex of invertebrate and vertebrate pests. Snails, slugs and false wireworms are long-standing issues, the severity and geographic distribution of which seem to be increasing. The associated increase in pesticide use has influenced pest complexes and accelerated selection pressure for resistance. Emerging invertebrate issues include weevils, bronzed field beetles, earwigs, millipedes and slaters.

Mouse plagues have increased in frequency as a result of stubble retention, a range of diverse crops, reduced cultivation, and reduced grazing pressure from livestock. This has led to both an increase in mouse numbers and greater damage for the same number of mice. Whereas during the past mouse plagues occurred every 6 to 7 years (before 1970), they are now likely to occur once every four years. Changes in cropping systems have not only improved feed supply and quality, they have provided a longer time period during which high quality food and shelter are available. Also mouse plagues are now reported in consecutive years, which rarely occurred historically.

Herbicide efficacy is a challenge in stubble retained systems where the stubble can interfere with the application of herbicides. Herbicide retained on stubble can volatilise, breakdown or wash onto the soil with subsequent rainfall. For pre-emergent soil applied herbicides, increased water volumes (100 -150 L/ha) are recommended in order to get more herbicide to the soils surface. Higher ground speeds at sowing can be accompanied by 'soil throw' from tined implements. Soil from the sowing row is thrown to the inter-row space reducing the effective rate of application of soil applied herbicide near the seed and increasing effective application rates in the inter-row space. The combination of wide row sowing and higher ground speeds at sowing have enabled higher application rates of pre-sowing soil-applied herbicides.

In addition, some useful herbicides are limited to a maximum of 50% groundcover of stubble, which is well below the stubble loads experienced in commercial cropping systems. Furthermore, there are proposals that could lead to regulation of useful chemicals and could see their loss from agriculture.

Conservation farming systems rely heavily on herbicides for weed control, and this has led to the evolution of herbicide-resistant weeds in southern Australian cropping areas. Non-chemical weed control offers an alternative control as part of an integrated weed management (IWM) system. Non-chemical methods of weed control can include cultivation, burning stubble, in-crop competition with weeds and collection of weed seeds in the harvester and their subsequent destruction. Other options include forage conservation, or green and brown manuring of paddocks, often with legume crops. These crops are then either incorporated by cultivation or, in the case of brown manuring, sprayed with non-selective herbicides before herbicide-resistant weeds set seed.

Conservation farming practices that retain stubble on the soil surface do not involve tillage. However, the sustained use of no-till can create problems in some situations, including stratification of nutrients, inability to incorporate lime and herbicides, increased pest populations (for example, slugs), inability to manage herbicide-resistant weeds, increased disease incidence, consecutive high stubble loads and soil compaction by livestock. Strategic tillage could have a place in conservation farming systems to ameliorate the effects of no-tillage. But there is concern that some benefits of no-till are cumulative, and cultivation could eliminate or reduce these benefits.

This review of stubble retention in cropping systems in southern Australia has identified potential gaps and opportunities in extension of disease diagnosis and clarification of the effects of no-till on SOC. Development and research gaps exist in (1) understanding the effects of stubble and stubble arrangement on storage of soil moisture and nitrogen cycling, (2) improving herbicide efficacy and (3) the evaluation and adaptation of the destruction of weed seed at harvest in the GRDC southern region. Further advances in inter-row sowing as a technique for areas of high and medium rainfall is a topic that provides opportunities which may enhance herbicide efficacy, improve moisture storage and increase grain yield.

GLOSSARY OF TERMS

Burnt stubble - Stubble can be burnt at any time from immediately **post-harvest** to just **before sowing**. The burn from immediately post-harvest to early autumn is frequently referred to as a ’hot burn‘ and the burn just before sowing is referred to as a late autumn burn or a ’cool burn‘. The terms ’hot‘ and ’cool‘ burn are avoided in this review as they are ambiguous. In fire fighting a ’hot‘ burn is considered as a grass fire with flame height >1.5 m and a ’cool‘ burn is a fire with flame height <1.5 m.

Conservation farming - Conservation farming promotes minimal disturbance of the soil by tillage and maintenance of groundcover by plants or their residues. Conservation farming aims to conserve soil and water by using surface cover (mulch) to minimise run-off and erosion and improve the conditions for plant establishment and growth. It involves planting crops and pastures directly into land which is protected by a mulch using minimum or no-tillage techniques.

Grazed stubble - Stubble which is grazed by livestock between harvest and sowing. Grazing intensity can vary from light grazing, where the intent is to utilise available feed in the stubble for the benefit of livestock while maintaining substantial groundcover, to heavy grazing where the intent is substantial removal of stubble. Light grazed stubble can be included as **retained stubble**, while heavy stubble is considered to be **stubble removal** or reduction.

Incorporated stubble - Incorporated stubble is buried or partially buried by cultivation with a disc ploughing or tined implement (such as a scarifier), where a substantial proportion of stubble is buried. A disc buried an average of 62% of stubble by weight in one pass (Sallaway *et al.* 1988).

Intact stubble - Intact stubble is undisturbed after harvest and is retained after sowing. This may disregard spraying operations to control weeds during summer. This may be referred to as **full stubble retention** or **standing stubble**. In practice '**standing stubble**' is partially flattened by the harvest operations (including harvester, chaser bins and trucks).

Mulched stubble - Stubble which has been mechanically treated and forms a layer on the soil surface.

No-till and zero-till - 'No-till' refers to crops sown with between 5 and 20% of soil disturbed and no prior cultivation, and '**zero till'** refers to sowing crops with < 5% of the soil disturbed (for example, disc seeded). These terms are sometimes used to imply full stubble retention, however, this is not always clear. For example, 20% of farmers regarded as no-till operators burnt stubble (Llewellyn and D'Emden 2009).

Retained stubble - Retained stubble present from harvest to sowing whether disturbed or undisturbed. This definition includes 'intact stubble' and stubble which have been flail mulched, slashed, harrow, crushed, rolled, incorporated or otherwise mechanically treated. This usually includes stubble which has been lightly grazed. The stubble is present after sowing.

Stubble removed - Stubble removed from the paddock other than by burning. This can be achieved by a low cutting height and baling of the residue at harvest, by windrowing at harvest and subsequent removal or by cutting post-harvest and removal (**'windrowed and removed**' see below).

Surface retained stubble - Stubble retained on the soil surface, including **intact, mulched** and **retained stubble,** other than **incorporated stubble**. This term is commonly used to indicate the stubble was substantially on the soil surface even though the soil was cultivated. This can be achieved by using rod weeders or by cultivating with widely spaced tines using wide sweep points. In the research of Sallaway *et al.* (1988) a blade plough retained an average of 83% of the stubble on the soil surface.

Windrowed and burnt - The residue from the harvester is placed in a narrow windrow (50 to 80 cm wide) at harvest and burnt the following autumn. The aim is to place harvested weed seeds in the windrow and to destroy them with a high temperature burn while leaving stubble across the rest of the paddock. A similar technique has been used to destroy snails which are encouraged to shelter in windrowed harvest residue, particularly during hot weather, and are then destroyed by burning the windrow.

1. INTRODUCTION

This review is intended to update the 2010 Graham Centre Monograph 'Stubble Retention in Cropping Systems in Southern Australia: Benefits and Challenges' (Scott *et al.* 2010). The present review expands on recent research data and extension materials from the past few years for south-eastern Australia, including the results from GRDC funded grower groups. It also includes some issues not addressed in the original monograph.

Eight years of dry seasons, leading up to 2010, affected much of the GRDC southern region (central and southern New South Wales (NSW), Victoria, Tasmania and South Australia (SA); Figure 1), which made moisture conservation a priority for growers. During this period stubble retention was generally well adopted, with the aim of conserving moisture. Adoption was not inhibited as the stubble loads were lighter and more manageable than those in subsequent years with higher rainfall and yields.

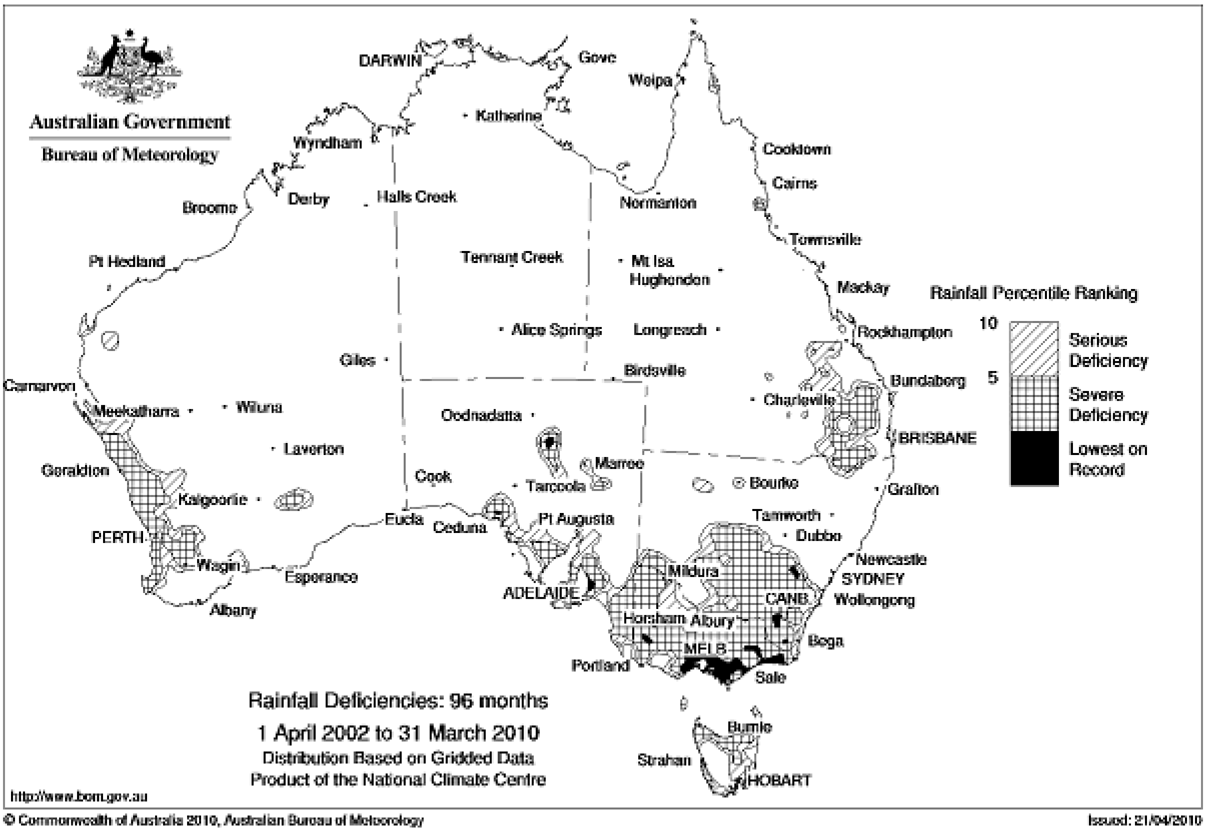

Figure 1. A large proportion of the GRDC southern region in southern New South Wales, Victoria, Tasmania and south-east South Australia was affected by serious rainfall deficiencies from 2002 to 2010. (*Source:* Bureau of Meteorology, 2012)[1].

During the years 2010 and 2011 above average rainfall and heavier stubble loads have seen growers forced to burn stubble to address management issues including machinery trash flow, poor crop establishment, herbicide resistance and pest and disease problems. Machinery development and stubble handling have become key priorities for growers aiming to maintain full stubble retention in their farming system.

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[1] © Commonwealth of Australia 2013, Bureau of Meteorology (ABN 92 637 533 532)

Recently published data suggest 50-60% adoption rates of stubble retention farming during 2011 in south-eastern Australia (Edwards *et al.* 2012), but with the challenges presented above, implementation of full stubble retention is likely to vary seasonally.

This review identifies current challenges in stubble management and highlights the gaps in knowledge. It will serve as a guide for stubble projects undertaken by GRDC funded grower groups.

1.1 Trends in implementation of full stubble retention

History and NRM origins and focus

Up to and including the early 2000s the emphasis for conservation farming had been natural resource management (NRM) gains or issues and fuel and labour savings, with erosion mitigation and soil protection being the main drivers for implementation of stubble retention practices. With the reduction in development and extension investment by state agriculture departments since the 1990s, many programs promoting stubble retention were undertaken by farmer-driven and NRM organisations with funding through Federal Government programs such as Caring for Our Country[2]. These programs fostered on-ground action, and farmer innovations, but in most cases they did not include a research (data gathering and analysis) component. The focus was farm-scale demonstrations, farmer-driven activities and production of regional best management practice guidelines emphasising the NRM benefits of stubble retention. The regionally targeted funding of most projects affected the geographical dissemination and access to information.

While the NRM initiatives fostered commitment among conservation farming advocates they have not provided the compelling evidence needed to persuade mainstream growers of the need to change from the traditional practice of burning stubbles to full stubble retention. Very few of the research trials conducted in the last decade have convincingly demonstrated the economic benefits of full stubble retention (Kirkegaard 1995; Scott *et al.* 2010). In fact, growers in the GRDC southern region have been presented with inconclusive and often conflicting information on the impact of full stubble retention on grain yield.

Frequency of full stubble retention

Steed *et al.* (1994) proposed that utilisation of crop stubble as a resource was the obvious 'next step' in the evolution of conservation farming in the cropping systems of south-eastern Australia. However, Kirkegaard (1995) concluded that "conservation farming techniques were not developed to increase yields" and that additional expected benefits, such as protection of the soil resource, timeliness of the sowing operation, fuel and labour efficiencies were difficult to quantify. Furthermore he predicted that adoption of practices such as full stubble retention "is likely to remain low in some regions if no long-term yield advantage can be demonstrated".

Pannell *et al.* (2006) proposed that "conservation practices that are not profitable at the farm level will tend to be adopted only by farmers with stronger conservation goals" and importantly, for "those farmers with a focus on profit, the farm-level economics of a proposed conservation practice will be important". Pannell *et al.* (2006) considered 'trialability' and 'relative advantage' the characteristics of an innovation most important in

[2]The Federal Government Caring for Our Country program superseded the National Landcare Program in 2007

driving adoption. Neither of these has been evident in the majority of projects promoting the advantages of full stubble retention.

When the Australian Bureau of Statistics (ABS) data from 2000/2001 and 2007/2008 (Figure 2) are considered in conjunction with stubble management data from the 2008 GRDC Farm Practice Baseline Report (Table 1), the 'adoption' of full stubble retention and a corresponding decline in the proportion of stubble burnt in the Southern region appears to match the typical diffusion of innovation trends presented by Rogers (2003). A fall from a frequency of 30% stubble burnt[3] recorded for NSW, Victoria and SA in 2001 to less than 5% in 2008 suggests that full stubble retention was widely adopted in 2008 and was the desired stubble management outcome for the majority of growers.

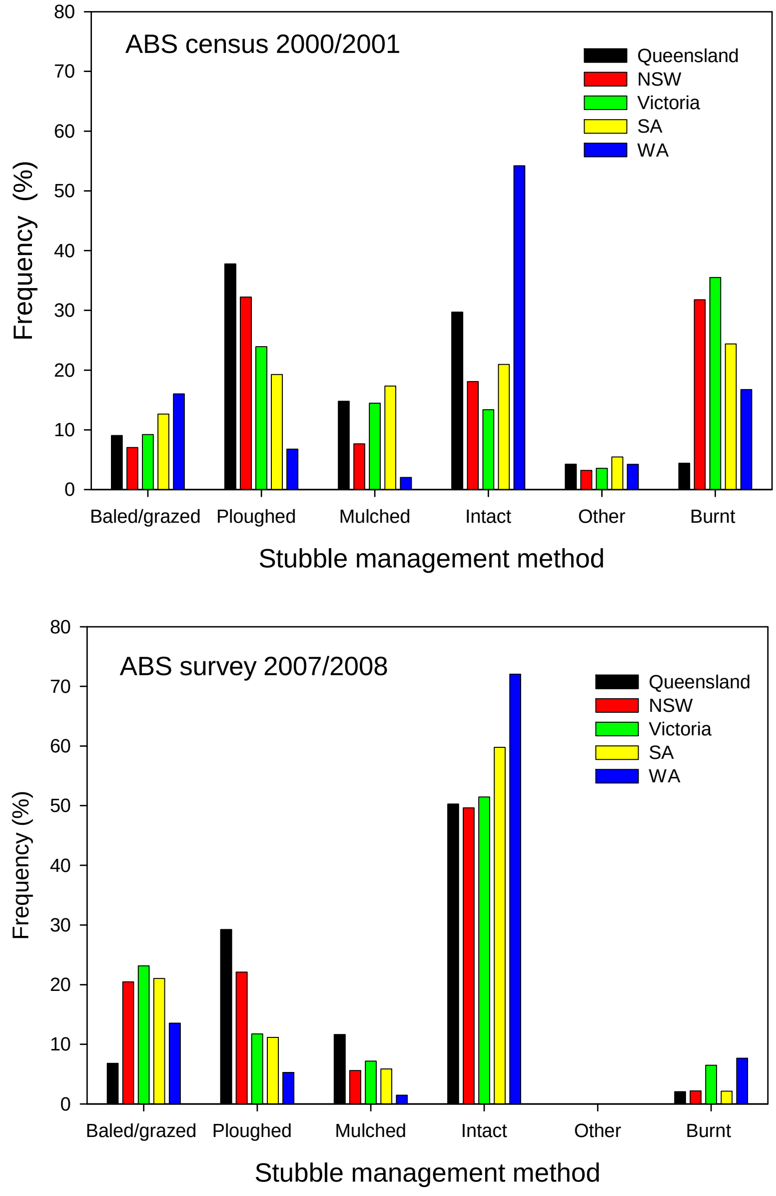

Figure 2. A comparison of 2001 and 2008 stubble management methods highlights the increase in stubble retention and decrease in stubble burnt in New South Wales, Victoria and South Australia.

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[3] Frequency of stubble burnt is used as an indicator of frequency of full stubble retention due to the ambiguity of terms used to describe 'stubble retained'

However, recent consultation by the authors with growers in the medium to high rainfall zones of southern NSW, indicate that while stubble retention over summer and early autumn is widely adopted, retention of intact stubble through to planting is not. This is demonstrated by the increased frequency of crop stubble burnt in 2011 as high as 35.7 to 42.5% in the Tasmanian, NSW/Victorian Slopes and Victorian High Rainfall zone (Table 1), which indicates that many growers in the GRDC southern region do not routinely implement the practice of full stubble retention across their cropping area (i.e. few growers have 'adopted' full stubble retention.)

Table 1. The percentage of stubble retained or burnt in agro-ecological regions of the GRDC in 2008 and 2011 as reported by growers responding to farm practice surveys conducted by GRDC (from Kearns and Umbers 2010; Edwards *et al.* 2012), reprinted with permission[4].

	2008		2011	
	Stubble retained (%)	Stubble burnt (%)	Stubble retained (%)	Stubble burnt[a] (%)
Northern Region				
QLD Central	94.4	0	68.3	5.1
NSW NE/QLD SE	95.2	3.4	69.7	7.5
NSW NW/QLD SW	98.8	0.1	76.9	11.5
Southern Region				
NSW Central	98.3	1.1	44.2	19.7
NSW/Victorian Slopes	92.3	2.3	60.6	40.5
SA Mid Nth, Lower EP	95.5	1.7	66.1	13.3
SA/Victoria Bordertown Wimmera	92.4	3.4	54.3	25.1
SA/Victorian Mallee	97.3	0	67.9	13.0
Tasmania	79.0	0	41.4	35.7
Victorian High Rainfall	96.1	1.7	37.0	42.5
Western Region				
WA Central	93.3	5.4	54.5	8.2
WA Eastern	87.2	12.8	66.0	2.0
WA Mallee/Sandplain	98.2	0.3	67.6	1.5
WA Northern	93.3	3.2	72.8	11.1

[a]Stubble burnt in the 4 weeks before sowing

It may be concluded from the 2011 survey data that many growers in the GRDC southern region have reverted to the traditional stubble management practice of burning stubble before sowing. However, these data do not reflect the widespread acceptance of the NRM benefits of stubble retention and the increased capability of many growers who achieved full stubble retention on a significant proportion of their cropping area under the extraordinarily wet seasonal conditions that affected the southern region in 2010/2011. In reality consultation with growers and advisors by the authors suggests that the reversion to burning as a stubble management option and the apparent dis-adoption of full stubble retention in 2011 (Edwards *et al.* 2012) should be considered as a temporary shift in management practices in response to

[4] Grains Research and Development Corporation (2010, 2012), 12 November, 2013.

a combination of issues arising from exceptional seasonal conditions, and not a shift in grower attitude to the benefits or otherwise of full stubble retention.

Drivers of full stubble retention and the emerging role in moisture conservation
Past reviews and studies have investigated factors that have affected adoption of conservation farming systems in the cropping and mixed farming zones of southern Australia (Haskins 2006; Pannell *et al.* 2006; Llewellyn and D'Emden 2009).

It is possible to identify the underlying reasons for the recent trends in the implementation of full stubble retention by assessing recent Australian Bureau of Statistics (ABS) surveys, the GRDC farm practice reports (Kearns and Umbers 2010; Edwards *et al.* 2012), NSW farm-scale demonstration projects and case studies (Holding 2010), the 2010 Graham Centre Forum (Burns *et al.* 2010), regional surveys (Davis 2006; Hufton, pers. comm.) and a 2011 case study of grower response to the challenging seasonal conditions of 2010/2011 (Burns *et al.* 2013). Brief overviews of each of the regional studies are presented in Appendix 1.

These regionally focussed studies provide an insight into the impact of economic, climatic and technological changes on stubble retention practices, particularly the grower response to the Millennium Drought from 2002 to 2010 (Figure 1) and contrasting conditions in 2010/2011. While these studies relate to south-east NSW they are relevant to other zones of the southern region.

The impact of the Millennium Drought on growers' approach to stubble management cannot be underestimated. This prolonged drought appears to have prompted investigation of the potential moisture conservation benefits of full stubble retention in southern NSW, where traditionally incident rainfall during the crop growing season had been the major contributor to crop water supply (Scott *et al.* 2010). The Bureau of Meteorology (2012) reported below average rainfall across much of the GRDC southern region from 1997 until early 2010. The below average growing season rainfall and resultant drying soil moisture profile created uncharacteristic soil moisture deficits for winter crop production and opportunity to present yield benefits (and the relative advantage) of implementation of full stubble retention through to planting.

Haskins (2006) reported conservation of soil moisture as a major impetus for increased adoption of conservation farming practices in the low rainfall zone of southern NSW from 2002. However, there appears to have been a delay in growers' interest in the potential for moisture conservation benefits from full stubble retention in the higher rainfall zones of NSW. In fact, the 2005 Harden Murrumburrah Landcare Group survey (Koen 2005) did not even include moisture conservation as an optional response to the question asking the main reasons for retaining stubble. While the NRM-focussed drivers of erosion prevention, organic matter build-up and nutrient retention were all optional answers, just 2 of the 42 growers responding to the survey independently nominated 'moisture retention'. However, moisture conservation and improved water use efficiency were nominated as reasons for adoption of full stubble retention by all growers participating in a 2011 case study which included growers from the medium to high rainfall zones of south-east NSW (Burns *et al.* 2013). Moisture conservation, reduced erosion, groundcover and nutrient retention were the perceived benefits of full stubble nominated by most growers contributing to the case study. Other benefits included:
- Improved soil structure.
- Improved soil health.

- Timeliness of the sowing operation.

The stubble management issues facing growers during the 2010/2011 season were in stark contrast to those of the Millennium Drought. Areas of the medium to high rainfall zones of southern NSW recorded rainfall from September 2010 to April 2011 of between 230 and 330% of the long-term average (Figure 3). The weed, pest and disease pressures and the practicalities of sowing into heavy stubble loads in 2011 presented a combination of challenges not experienced for many years (Burns *et al.* 2013). This prompted a case study of growers experienced in full stubble retention to gauge changes in their approach to stubble management.

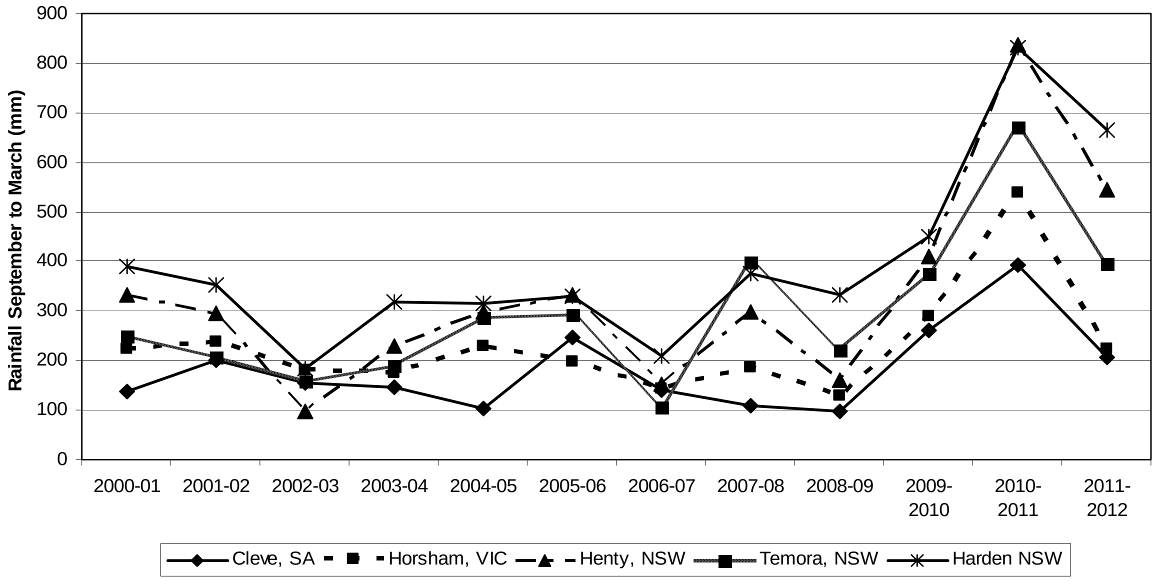

Figure 3. Rainfall recorded for the spring, summer and autumn periods (September to March, inclusive) from 2000 to 2012 at Henty, Temora and Harden in southern New South Wales, Cleve in South Australia and Horsham in Victoria.

The case study (Burns *et al.* 2013) provides an insight into the high level of management required to achieve full stubble retention in 2010/2011. The study indicates that the decision to burn stubble was based on each grower's assessment of the costs of implementing practices aimed at full stubble retention under extreme conditions, compared with the benefits to be gained by burning a proportion of the stubble area. It follows that the increase in frequency of burning and apparent dis-adoption of full stubble retention reported by Edwards *et al.* (2012) is likely to have been a rational and sensible strategy, as proposed by Vanclay (2004). This summation applies particularly for next-generation growers and advisors with limited experience in full stubble retention. The case study suggests that even growers with over 20 years of experience and commitment to full stubble retention considered that burning was the best management option when faced with a combination of issues, including heavy stubble loads and disease, weed and pest pressures.

Management demands and regular implementation of full stubble retention

Llewellyn (2011) described no-tillage systems as "information intensive and potentially complex", and Steed *et al.* (1994) proposed that growers choosing to implement full stubble retention "need to learn new methods of crop production which require a high level of management". Findings from consultation and the regional studies suggest that full stubble retention presents a level of complexity above no-tillage systems and one that demands a high management capacity if it is to be implemented routinely across a range of potentially highly variable conditions.

The level of complexity was evident at the 2010 Graham Centre Stubble Forum (Burns *et al.* 2010). Experienced growers who attended the Forum stressed that success of full stubble retention systems required implementation of strategies aimed at avoiding issues that place undue pressure on the 'system'. They proposed that long-term planning, diverse crop rotations and diligent variety selection, and monitoring of weed, pest and disease populations were essential. Underlying the success was a level of confidence arising from experience and a sound understanding of agronomic principles, and a capacity to make timely and tactical decisions in response to changing conditions. This required an ability to predict, recognise and respond early to triggers so as to avoid issues that could impact on yield potential and profitability. These growers considered that full stubble retention was unsustainable for growers with a reactive management style.

The regional studies indicated that the suite of technologies implemented to manage stubble will vary spatially and temporally and is likely to be influenced by prevailing conditions and management issues presented at the regional, farm and paddock level. At the individual grower level, experience, knowledge (their own and that of technical specialists and advisors) and capital investment in specialist equipment will also determine the technologies and practices implemented. For the majority of mainstream growers the decision on whether to fully retain stubble often lacks long-term planning and is likely to be based on a year by year analysis of the best course of action to ensure the optimum outcome for their business and personal goals (social and environmental).

These observations were reinforced by the case study of 15 growers from the medium to high rainfall zone of NSW (Burns *et al.* 2013). Many of the growers participating in this study had participated in the 2010 Graham Centre Stubble Forum and the Cereal Stubble Management Project (Holding 2010). Experience with stubble retention varied from two to 28 years, with all the growers demonstrating a level of commitment to conservation farming. Thirteen aimed for full stubble retention across their cropping area, while the remaining two growers had a pragmatic approach to stubble management, that is, although they had invested in specialist machinery with capacity to sow into stubble, they used burning routinely to manage heavy stubble loads, particularly in the establishment of small-seed crops (for example, canola) or as a weed management strategy.

Consequently the stubble management decisions each of these growers made in 2010-2011 were unique to the individual and were influenced by the combination of experiences, cropping systems, agronomic and logistic challenges, and commitment to full stubble retention. Of the 15 growers involved in the case study only four burnt stubble in 2010, amounting to 11.5% of the crop area sown by all participating growers. In 2011, however, 11 growers burnt a proportion of stubble to ensure successful crop establishment. Even growers with more than 10 years of experience implementing full stubble retention chose to burn up to 90% of their cropping area. One grower who had not burnt stubble for 28 years commented that the alternative was total crop failure.

The area of stubble burnt in 2011 by the growers participating in the case study amounted to 41% of their combined cropping area (Burns *et al.* 2013), which aligns with the 40.5%

reported for the NSW/Victorian Slopes GRDC agro-ecological in the 2011 GRDC survey (Edwards *et al.* 2012) (Table 1).

Vanclay (2004) proposed that a grower will implement technologies (that may or may not have full stubble retention as an outcome) if they perceive the technology will benefit their business. It is apparent from the case study, the 2010 Graham Centre Stubble Forum and the authors' experience that growers will make an intuitive benefit/cost assessment on a paddock by paddock basis (and even within zones in a paddock) and select from technologies and practices at their disposal that they consider will ensure crop establishment as a priority and provide the least risk to profitability. The decision to burn comprises an assessment by each grower of the perceived benefits of full stubble retention (soil condition and protection and moisture conservation) weighed against the perceived potential costs, both biophysical (weeds, disease, pests, stubble loads) and logistical (from the harvest process through to successful seedling establishment).

The findings of the case study (Burns *et al.* 2013) support the conclusions of Vanclay (2004): that growers respond to complex innovations (such as full stubble retention) by managing the complexity in components, with growers choosing those components that they consider they are able to manage and that will assist them in achieving their goals and objectives.

Grower response at the Graham Centre Stubble Forum, the Cereal Stubble Management Project (Holding 2010) and 2011 case study (Burns *et al.* 2013) suggest the use of burning is viewed by many growers as one tool among the suite of technologies that they may implement to avoid issues that they perceive will compromise the profitability of the subsequent crop. This is demonstrated by the reasons given by the case study participants for the increase in the area of stubble they burnt in 2011:

- Trash handling difficulties and risk of delayed sowing.
- Potential impact of heavy stubble loads on crop establishment, in particular canola establishment[5].
- Herbicide efficacy, in particular the perceived risk of poor efficacy of pre-emergent herbicides.
- Weed management, arising from inability to control intercrop weed populations, and implementation of burning as a strategy to minimise risk of herbicide resistance
- Disease risk, particularly where wheat was being sown into wheat stubble.
- Pest risk (the survey coincided with a mice plague in the region).

The majority of growers participating in the case study considered they had lost minimal long-term benefits accrued over years of stubble retention as a result of burning stubble in 2011. A one-off burn was considered to have multiple benefits, and assist in the management of excessive stubble loads and weed, disease or pest issues for which there were no reasonable alternative management options.

Segmentation of the grower population on approach to stubble retention

The fluctuation in frequency of stubble burning in 2008, during the Millennium Drought, and in 2011 (Table 1) suggests that a large proportion of growers in the southern region will opportunistically retain stubble. However, the regional surveys and consultation process indicates variable capacity and commitment of individual growers to manage multiple

[5] Dry matter of wheat crop residue ranged from 4.0 t/ha measured immediately after harvest in the low medium rainfall area of Mirrool Creek, up to 10.7 t/ha in header trails at Henty in demonstration plots of the Cereal Stubble Management Project (T. Pratt, pers. comm.)

components of complex stubble retention ‘systems’. Findings from regional surveys and studies (Holding 2010) indicate that growers’ approach to full stubble retention is very diverse.

Growers participating in the Cereal Stubble Management Project, the case studies and the Graham Centre Forum demonstrated a confidence in the long-term benefits of full stubble retention and value the NRM outcomes in achieving their long-term profitability and sustainability targets. As proposed by Vanclay (2004), adoption of a new technology (in this case full stubble retention) has occurred because there is "thorough belief that the benefits outweigh(ed) the costs".

This group of growers also fits the description of active partakers of technology described by Glyde and Dunn (2006), growers who have committed significant investment in stubble management equipment and intellectual capital. They actively seek and research information from multiple sources and are likely to employ consultants to hone their agronomic skills. They have a demonstrated willingness to trial and adapt new technologies and value the learning process that builds on their knowledge and experience. As noted by a grower at the Graham Centre Forum:

> *“I want access to the research…I do not want the recommendations and interpretations of the research presented in a package”*

The Millennium Drought appears to have prompted many mainstream growers targeting improved efficiency in productivity to look more closely at full stubble retention and the potential benefits from improved water use efficiency, labour savings and conservation of nutrients. These opportunities have attracted the next tier of growers to consider and opportunistically implement full stubble retention.

Prior to the recent advances in technologies, Steed *et al.* (1994) proposed that the majority of growers would be "reluctant to change systems because of the need to learn completely new methods of crop production" as new technologies required "specialised knowledge, machinery and expertise". However, Llewellyn *et al.* (2012) proposed that the adoption of enabling technologies such as disease resistance, selective herbicides and fungicides, GPS guidance systems (for inter-row sowing) and specialist sowing equipment have reduced knowledge requirements and simplified management. From the regional studies it is apparent that those technologies have enabled less experienced growers to fast-track implementation of full stubble retention and achieve a level of conservation farming that meets their desired objectives without the need for a thorough understanding of the 'system'.

However, the authors’ experience suggests that implementation of full stubble retention among the less experienced growers is likely to be spasmodic and opportunistic. They are likely to revert to stubble burning when enabling technologies are ineffective. These growers are likely to lack the experience and/or management capacity to integrate the multiple system components under challenging circumstances and would rely on support from technical specialists and advisors to navigate the complexities when faced with multiple issues.

Variability of grower skill sets and interest in developing knowledge and expertise was highlighted in the 2005 Harden-Murrumburrah Landcare Group survey (Koen 2005). When asked the reason for burning stubble, 34% of growers involved in this survey nominated ‘management ease’. Further analysis of the survey results indicated that those growers who nominated management ease as a reason for burning stubble did not select any other option that required management skills or expertise, such as stubble handling, disease or weed management. These growers may not have the inclination, knowledge of agronomic principles and/or experience to integrate the system components without considerable support from advisors. However, as indicated by the large proportion of stubble retained in 2008 (Table 1), the majority of mainstream growers will retain stubble when it is perceived to be the strategy most likely to benefit crop yield.

The role of embodied and enabling technologies in the widespread adoption of no-tillage systems was raised by Llewellyn (2011) and Llewellyn *et al.* (2012). However, adoption of these technologies does also create significant risks for the intensive wheat-canola based cropping systems widely adopted in southern Australia. This is particularly the case when 'silver bullet' technologies are being used as a surrogate for sound agronomic management. In terms of crop disease, Stukenbrock and McDonald (2008) warned against "dense and uniform host populations" and suggested that a "vast scale of agro-ecosystems select for highly specialised and aggressive pathogens". This conclusion may be applied more broadly to pest and weed populations.

The regional studies indicate that a relatively small proportion of growers actively seek diverse strategies and operate robust cropping systems with an integrated management approach that involves a combination of enabling technologies and sound agronomic principles. The majority appear to rely heavily on enabling technologies and operate systems that lack diverse management strategies. Therefore it is reasonable to expect continued fluctuations in the frequency of burning in response to variable climatic conditions, varying stubble loads and incidence of weed, disease and/or pest pressure, particularly when the efficacy of these enabling technologies is challenged.

Monitoring adoption of stubble retention
Remote sensing has been used to attempt to estimate stubble amount and groundcover (Aguilar *et al.* 2012). While this attempt was unsatisfactory, there remains scope to improve estimates. A second approach would be to use remotely-sensed data on estimate vegetative growth to provide a crude estimate of stubble amount by assuming a harvest index. Crop burning during autumn and early winter can be remote sensed using the MODIS satellites.

1.2 Stubble management and farming systems

The benefits of conservation farming are assumed to accrue through improved soil health with subsequent benefits to crop yield and quality, or reduced inputs to the farming enterprise. These benefits may be true if in a mixed farming system the ratio of crop to pasture is stable. However, evidence of this stability is not the case, with many farming systems having an increasing number of cropping years and fewer pasture years. This trend has been noted by Kirkegaard *et al.* (2011) and Fisher *et al.* (2012). Any advantage of conservation farming is not expressed as improved soil health, but as the potential for more cropping.

Godyn and Brennan (1984) identified the economic benefit that may accrue from extending the cropping phase by one year by using direct drilling. Of course the economic benefits would be a function of the relative profitability of cropping compared with livestock production. However, an intensification of cropping has been reported on the Lower Eyre peninsula of South Australia (Tolhurst *et al.* 2008). This increase in cropping combined with the decrease in pasture and area under cultivated fallow were regarded as contributing to an increased wildfire risk over the summer, as exemplified by the Wangary (Eyre Peninsula) fires during 2005 (Tolhurst and Egan 2008; Tolhurst *et al.* 2008).

Of the 17 experiments reviewed by Kirkegaard (1995), where stubble retention was compared with stubble removal or burning, only two had treatments with some pastures (Wagga Wagga and Tarlee); others had exclusively continuously cropped treatments. The scarcity of experiments involving pastures demonstrates the inclination for no-till, stubble-retained systems to be investigated, and subsequently promoted, in continuously cropped systems.

1.3 How much stubble is there?

Advisory guidelines frequently echo the view that stubble loads after harvest can be estimated as being 1.5 times the yield of grain (for example, Anon 1985; Bowman and Scott 2009). However, many publications avoid such a generalisation (Robinson 1998; Anon 2011d).

Table 2 below was drawn from a long-term experiment at Wagga Wagga NSW (SATWAGL). The long-term average grain yield of wheat was 3.4 t/ha with an average stubble yield post-harvest of 7.7 t/ha (range 2.5 to 11.2 t/ha). The quantity of post-harvest stubble after lupins was 6.1 t/ha (1.5 to 15.8 t/ha) and for canola was 7.2 t/ha (2.2 to 11.5 t/ha).

Table 2. Grain and stubble yields, with derived harvest indices, for wheat (27 seasons), lupins (27 seasons) and canola (12 seasons) from a long-term experiment at Wagga Wagga, New South Wales. The data for wheat is also presented in Figure 4.

Crop type	Measured grain and stubble yields (t/ha) and derived harvest indices								
Wheat									
Grain yield	0.5	1	1.5	2	3	4	5	6	7
Stubble yield	3.4	4.2	5.0	5.7	7.1	8.4	9.5	10.5	11.4
Harvest index	0.13	0.19	0.23	0.26	0.30	0.32	0.34	0.36	0.38
Lupins									
Grain yield	0.4	0.8	1.2	1.6	2	2.4	2.8	3.2	3.6
Stubble yield	3.4	4.3	5.2	6.1	7.0	7.9	8.7	9.6	10.5
Harvest index	0.11	0.16	0.19	0.21	0.22	0.23	0.24	0.25	0.25
Canola									
Grain yield	0.5	0.8	1.1	1.4	1.7	2	2.3	2.7	3
Stubble yield	4.0	4.6	5.1	5.6	6.2	6.7	7.2	8.0	8.5
Harvest index	0.11	0.15	0.18	0.20	0.22	0.23	0.24	0.25	0.26

In reality a wide range of relationships exists between grain yield and stubble immediately post harvest (Figure 4). For example, a 2 t/ha grain crop in Queensland would appear to average about 1.8 t/ha of stubble, WA reports would give a stubble estimate of 3.6 t/ha for a similar grain yield, and at Wagga Wagga, NSW there would be 5.7 t/ha of stubble for a 2 t/ha wheat yield.

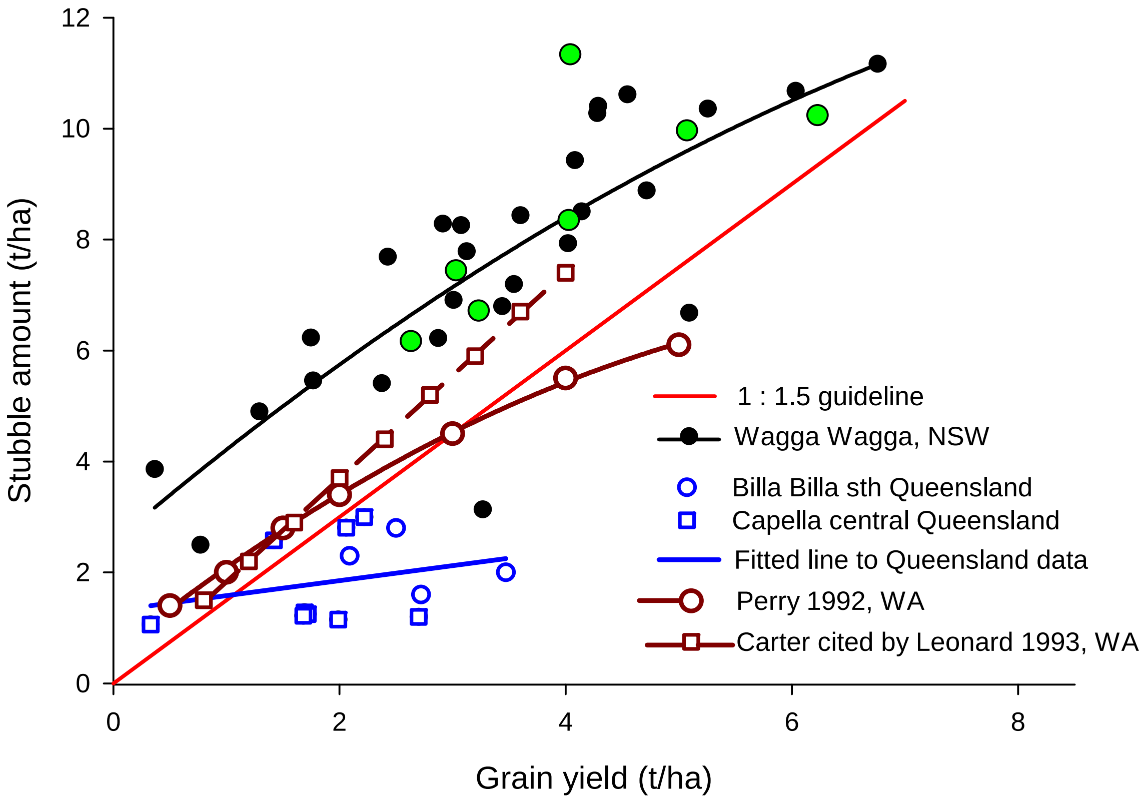

Figure 4. The relationships between amount of grain and amount of stubble for Wagga Wagga New South Wales over 27 years (Conyers pers comm; Heenan *et al.* 1994); Queensland based on data from central (three seasons and three cropping systems; Sallaway *et al.* 1988) and southern (four seasons; Radford *et al.* 1992) Queensland, and from reports in WA (Perry 1992; Carter cited by Leonard 1993) compare to the guideline that stubble is 1.5 times the grain yield. Data points in green are from southern New South Wales and north-eastern Victoria (Poole *et al.* 2011c, 2011d, 2012b, 2012c).

The second issue is the rate of stubble breakdown between harvest and the subsequent sowing. This rate will determine the stubble remaining when the next crop is sown and has been reviewed previously (Scott *et al.* 2010). In the southern cropping areas about 70% of stubble present immediately after harvest remains at sowing, but this is seasonally variable. In Queensland the breakdown of standing or surface stubble has been recorded as leaving 16% (Wang and Dalal 2006) or 43% (Cogle *et al.* 1987) of stubble by sowing. Based on other Queensland data (Sallaway *et al.* 1988) about 1.4 t/ha of stubble was lost on average (over three seasons and various cropping systems) between harvest and sowing. This was a loss of 15 kg/ha/day for the first 60 days, and 3 kg/ha/day for the remaining 164 days. Based on the amount of stubble present this would imply that between 0% and 53% of stubble remained at sowing; an average of 16%.

Using experiments covering a number of seasons and some assumptions (Table 3) it is possible to estimate the amount of stubble likely to be present at sowing for a number of sites across the Australian wheat belt (Table 3 and Figure 4). The same data is presented pictorially in Figure 5.

Table 3. Estimated amount of wheat stubble at sowing the following year for six sites in the Australian wheat cropping areas.

Site	Years	Source of grain yield data	Stubble post-harvest	Stubble at sowing	Frequency of ≥3 t/ha at sowing (%)
Wagga Wagga, NSW	27 years (1979-2005)	Conyers pers comm.; Heenan *et al.* (1994)	Directly measured	70% of post-harvest	89%
Condobolin, NSW	21 years (1979-1999)	Fettell pers. comm; Fettell and Gill (1995)	Perry (1992)	70% of post-harvest	29%
Merredin, WA	21 years (1979-1990 & 9 later years)	Jarvis (1987); Riethmuller pers. comm.	Perry (1992)	70% of post-harvest	19%
Wongan Hills, WA	12 years (1979-1990)	Jarvis (1987)	Perry (1992)	70% of post-harvest	0%
Warwick, Qld	8 years (1969-1979)	Marley and Littler (1989)	Figure 4	50% of post-harvest	0%
Billa Billa, Qld	10 years (1984-1993)	Radford *et al.* (1992)	Figure 4	50% of post-harvest	0%

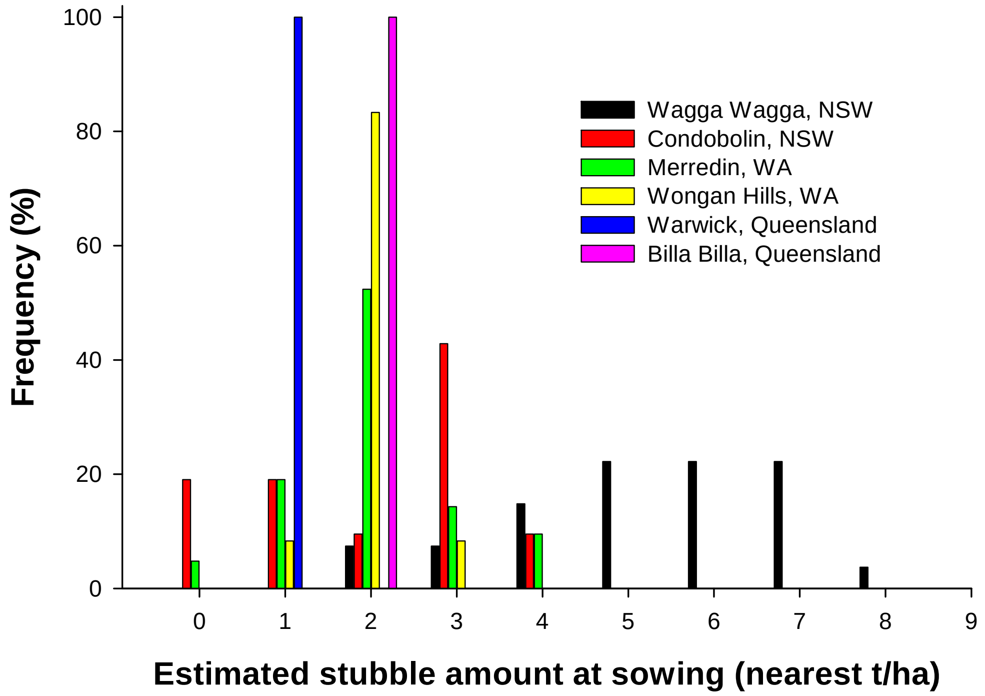

Figure 5. The estimated amount of wheat stubble at sowing to the nearest t/ha for six sites in the Australian wheatbelt based on grain yield with estimated stubble post-harvest, and loss prior to subsequent sowing (Table 3 for assumptions).

2. BENEFITS OF STUBBLE RETENTION

2.1 Reduced wind erosion

Long, standing stubble effectively reduces the wind speed at or near ground level. Recent evidence of this effect was provided by Mudge and Jeisman (2011). The wind speed at 20 cm above ground was reduced to 17-26% of the wind speed at 200 cm above ground by 35 cm standing stubble of wheat sown at 30 cm row spacing (Table 4). These results were similar to those reported for wheat stubble by Aiken *et al.* (2003). Mudge and Jeisman (2011) observed similar reductions of wind speed whether the wind was aligned along the wide rows (11 May, 2011 observations; 26%) or was crossing the rows at about a 65º angle (8 April, 2011 observations; 17%).

Table 4. Average wind speed observations (km/hr) at 200 cm and 20 cm above ground height, and wind speed ratio at Port Germein, South Australia on two measurement occasions in wheat stubble (4.5 t/ha) at three heights in 30 cm rows aligned SW-NE (from Mudge and Jeisman 2011), reprinted with permission[6].

	Observation date: 8 April, 2011 Wind: NNW gusting to 35 km/hr			Observation date: 11 May, 2011 Wind: SW gusting to 27 km/hr		
Stubble height (cm)	200 cm	20 cm	Wind speed ratio[A]	200 cm	20 cm	Wind speed ratio
5 cm	25.3	16.1	0.64	18.2	12.0	0.66
20 cm	20.3	8.7	0.43	17.1	6.6	0.39
35 cm	23.2	4.0	0.17	16.7	4.3	0.26

[A] Wind speed ratio = wind speed at 20 cm height/wind speed at 200 cm height

Lowering wind speed at the soil surface can reduce evaporation of moisture from the soil. Partial standing stubble (4.6 t/ha of stubble; 50% standing) was more effective than flattened stubble at reducing soil surface temperatures and moisture loss via reduced wind run (Smika 1983).

2.2 Improved water balance and increased soil water storage

The value of soil moisture

Seedbed moisture that allows early sowing can increase crop water use efficiency by 21-31% according to Kirkegaard and Hunt (2010) representing a 2-7% yield reduction for each week that sowing is delayed after the optimum sowing time (Anon 2011e; Matthews *et al.* 2013). At Wagga Wagga, NSW yield loss has been estimated at about 3.5% (about 0.17 t/ha) for each week delay in sowing from the last week of April (Kohn and Storrier 1970; Heenan *et al.* 1994). More recent data (Hunt *et al.* 2012b) identified yield loss in EGA Eaglehawk⊕ of 0.19 t/ha/week at Temora in 2011 and 0.25 t/ha/week at Junee in 2012 for delays up about a month after 15 April and 18 April, respectively.

Water stored deep in the profile is generally regarded as highly valuable to dryland crops because it becomes available during the post-anthesis period when grain yield is particularly sensitive to water deficit (Fischer 1979; Passioura 1983). Sadras *et al* (2012) highlighted

[6] Eyre Peninsula Farming Systems Group and first author (2011), 9 October, 2013.

evidence from Mediterranean environments that grain number was the main source of variation in yield and therefore the period between stem elongation and anthesis was a time when water supply was critical. French and Schultz (1984) stated that additional subsoil water can achieve a marginal water use efficiency of 59 kg/ha/mm, or three times the value for water use calculated on a whole-season basis (20 kg/ha/mm).

Other research also suggests that subsoil marginal water use efficiency (MWUE) in southern NSW can range from 0-60 kg/ha/mm (Condon *et al.* 1993; Angus 2001; Lilley and Kirkegaard 2007). Stored subsoil water is more likely to contribute to higher yields in higher rainfall environments due to its more frequent occurrence, and in above-average seasons due to its more efficient conversion to yield. At drier sites the reduced value of subsoil water resulted from infrequent profile wetting (Lilley and Kirkegaard 2007). In the Mediterranean environments of SA and Victoria stored soil water appeared to be of value in drier growing seasons; in wetter seasons (rainfall between sowing and harvest > 264 mm) stored soil water did not increase grain yield (Sadras *et al.* 2012). Crop modelling for Victoria (Hunt *et al.* 2013) and field trials in central NSW (Haskins and McMaster 2012) and SA (Sadras *et al.* 2012) have highlighted the conversion of stored moisture to grain yield could be limited by low nitrogen supply.

Summer fallow rainfall is of most value to wheat in environments where it makes up a greater proportion of annual rainfall, where fallow efficiencies are high, the soils plant available water holding capacity (PAWC) is large relative to growing season rainfall (GSR), and GSR is more variable (Hunt and Kirkegaard 2011).

Stubble and evaporation of stored moisture

Monzon *et al.*(2005; 2006) state that the effect of stubble mulch on soil water storage during fallow is highly variable. Research conducted via the GRDC WUE initiative found that stubble residues had only a minor impact on moisture retention (Mudge *et al.* 2009; Browne *et al.* 2011; Haskins and McMaster 2012; McClelland and McMillan 2012). For example, Browne and Jones (2008b); (2008a) found that 5 t/ha of wheat straw residue increased wheat yield by 0.2 t/ha, while Haskins and McMaster (2012) found no yield or moisture benefit from retained stubble residue (standing or flattened). Stubble architecture (standing or slashed) has been reported to have negligible impact on moisture conservation (Haskins and McMaster 2012; Sadras *et al.* 2012; Verburg *et al.* 2012; Hunt *et al.* 2013). These results are in contrast to major differences reported in Colorado, USA by (Smika 1983), where standing stubble was more effective in enhancing moisture storage during the fallow.

Table 5. The effect of standing or flattened stubble on soil moisture storage (PAW; mm) at sowing in the GRDC southern region.

Site (year; soil)	Stubble load, t/ha; (type)	Rainfall (mm)		Soil moisture storage at sowing (mm)		Reference
		Fallow rain	In-crop rain	Stubble standing	Stubble slashed	
Gunningbland, NSW (2010)	–	270	303	nr[a]	nr[a]	(Haskins and McMaster 2012)
Hopetoun, VIC (2009; sand)	2.7[b]	90	213	8	6	(Hunt *et al.* 2013)
Hopetoun, VIC (2009; clay)	2.4[b]	90	202	16	12	"
Hopetoun, VIC (2010; sand)	3.6[b] (barley)	224	264	70	79	"
Hopetoun, VIC (2010; clay)	4.4[b] (barley)	254	264	117	116	"
Hopetoun,VIC (2011; sand)	5.7[b] (canola)	387	198	97	113	"
Hopetoun,VIC (2011; clay)	5.2[b] (canola)	387	198	145	133	"
Wagga, NSW (2006)	4.0[c] (wheat)	109	–	45	44	(Verburg *et al.* 2012)
Hart, SA (2009)	2	160[d]	266	nr[a]	nr[a]	(Sadras *et al.* 2012)

[a]Not reported, but no significant differences in storage between stubble treatments
[b]Residue measured post-harvest
[c]Residue measured at sowing
[d]Rainfall and maximum irrigation

Hunt and Kirkegaard (2011) state that retaining crop or pasture residues on the soil surface improves fallow efficiency by minimising the physical impact of raindrops on the surface soil, maintaining structural integrity and infiltration rates, and reducing run off. Residues slow the flow of water on the soil surface, allowing for more time for infiltration as well as slowing soil evaporation following rainfall events. However if conditions remain dry for an extended period, total evaporation will be unaffected by residues.

Verburg *et al*. (2010a; 2010b; 2012) use a “pulse paradigm” to explain various impacts of residue retention on conserving moisture by considering soil water pulse size, frequency, duration and depth. Rainfall variability is viewed as different possible sequences of events that create pulses of water.

For a single rainfall event that creates a pulse of soil water, residue retention will only delay the loss of the infiltrated water by evaporation. Cumulative evaporation from the system with residue will catch up to that without residue if it is not followed by a second pulse (Figure 6). The same argument would hold when comparing systems with standing and flattened residue. This means that the benefits of residue management are determined by the soil water pulse size relative to the frequency. If pulses overlap, water can move further down in the soil in the delayed system (with residue) and this leads to stored soil water if pushed beyond the evaporation zone of the soil profile.

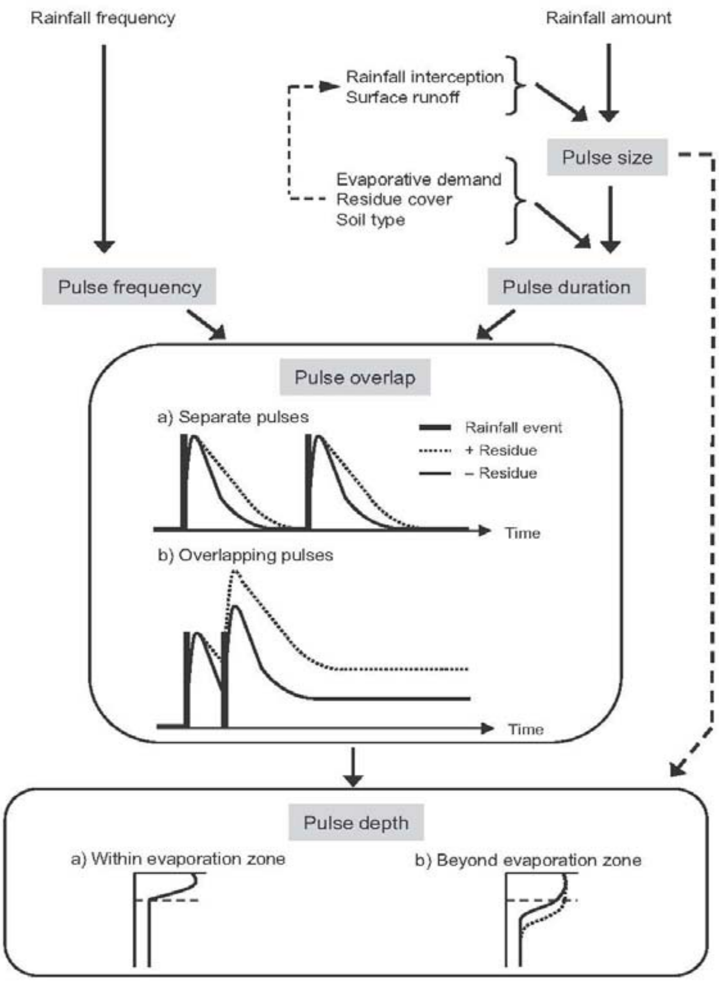

Figure 6. The pulse paradigm as applied to the impacts of residue management, adapted from Noy-Meir (1973) (from Verburg *et al.* 2012), reprinted with permission[7].

For residue management to create a lasting difference in the amount of accumulated soil water, the balance between pulse (rainfall) frequency and pulse size and duration must be such that successive soil water pulses accumulate or are caused to accumulate by the presence of residue cover thereby pushing some water beyond the evaporation zone. In summer, evaporative demand is very high and the water within the evaporative zone may be lost irrespective of stubble cover, before another pulse arrives.

Differences in stubble cover over summer have only a small effect on evaporative loss irrespective of stubble cover (Table 6). Even when burning of stubbles is practiced stubble is burnt in autumn/ early winter and the stubble is present over summer, as in stubble retention system. Evaporation demand needs to be relatively low (compared to rainfall amount and frequency) for residue cover to significantly affect evaporation. Larger differences in evaporation between stubble retained and stubble removed treatments occur with lower evaporative demand, typical of autumn/early winter (Table 6). The most crucial time for any increase in stored water due to retaining stubble is likely to occur from autumn, when stubble may be burnt, until canopy closure of the new sown crop.

Residue cover in autumn and early winter can make a significant difference in soil water accumulation; this effect was also observed by Browne and Jones (2008b; 2008a).

[7] ©Elsevier (2012), 15 October, 2013.

Table 6. Simulated 30-day evaporation difference between 4 t/ha stubble (retained stubble) and 0.4 t/ha (removed stubble) (from Verburg *et al.* 2012), reprinted with permission[8].

Rainfall events	High evaporative demand (6.3 mm/day January average)	Low evaporative demand (1.1 mm/day June average)
Frequent rainfall (15 x 3 mm)	0.7 mm	15.5 mm
Infrequent rainfall (5 x 9 mm	0.8 mm	15.1 mm
Single rainfall event (1 x 45 mm)	1.4 mm	14.0 mm
Double rainfall event (2 x 22.5 mm)	3.9 mm	14.2 mm

Soil moisture storage

Improvement in the capture and storage of water derived from tillage and stubble management depends on soil type, rainfall pattern and evaporative demand. Soils with higher clay content in the upper layers retain larger amounts of water in the surface layers and require larger rainfall events for water to infiltrate below the evaporation zone.

Most authors agree that the greatest and most reliable influence of tillage on fallow efficiency has been through weed control (Hunt and Kirkegaard 2011). The benefits of clean weed free fallows are that they have a relatively low cost for high potential returns as both moisture and nitrogen availability is improved for the following crop (Table 7) (Haskins and McMaster 2012). Sadras *et al.* (2012) discusses how nitrogen is critical to capture the benefits of additional summer water and reciprocally high water supply was required to capture the benefits of nitrogen fertiliser.

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Table 7. Experimental results from various WUE initiative sites showing additional pre-sowing plant available water (PAW) and nitrogen, crop yield and return on investment due to summer weed control. Return on investment assumes chemical and grain prices in the year of the experiment ($ return per $ invested) (adapted from Hunt 2013).

Site (soil type)	Year	Summer fallow rain (mm)	Additional PAW pre-sowing (mm)	Additional mineral N pre-sowing (kg/ha)	Sown crop	Additional yield (t/ha)	Yield with weed control (t/ha)	Return on investment in weed control
New South Wales NSW Department of Primary Industries & Central West Farming Systems								
Waroo	2008	358	*56*[a]	*25*	Wheat	*1.0*	*2.6*	*$12.00*
Gunningbland	2010	270	**53**[b]	**57**[b]	Wheat	**1.7**	**3.7**[b]	$5.67
Gunningbland	2011	488	**98**	**85**	Canola	**1.0**	**2.2**	$17.67
Tottenham	2010	417	**21**	**32**	Wheat	**1.4**	**2.4**	$4.67
Rankins Springs	2010	304	0	**57**	Wheat	**1.0**	**3.7**	$3.18
Rankins Springs	2011	384	-	-	Wheat	**0.7**	**1.7**	$9.91
Rankins Springs	2012	476	**62**	**88**	Wheat	**1.2**	**3.5**	$4.58
Condobolin	2011	290	NA	**36**	Wheat	**1.1**	**2.2**	$3.33
Condobolin	2012	461	**55**	**62**	Wheat	**0.5**	**1.7**	$2.61
Victoria Birchip Cropping Group & CSIRO								
Curyo	2008	76	24	**14**	Wheat	**1.3**	**2.5**	$5.00
Hopetoun (sand)	2009	90	11	-3	Barley	0.2	3.4	$1.20
Hopetoun (clay)	2009	90	3	10	Barley	0.3	2.8	$1.80
Hopetoun (sand)	2010	224	**40**	**45**	Canola	**0.4**	**3.1**	$4.76
Hopetoun (clay)	2010	254	**52**	**43**	Canola	**0.6**	**2.7**	$7.16
Hopetoun (sand)	2011	387	**29**	**41**	Wheat	**1.6**	**3.7**	$7.62
Hopetoun (clay)	2011	387	**36**	**53**	Wheat	**1.4**	**2.8**	$10.09
Hopetoun (sand)	2011	156	**42**	**44**	Lentils	**0.3**	**0.9**	$3.19
Hopetoun (clay)	2011	156	41	**55**	Lentils	**0.5**	**1.1**	$3.97
South Australia Upper North Farming Systems & CSIRO								
Quorn (heavy soil)	2009	175	10	-	Wheat	**0.2**	**1.3**	$0.98
Port Germein (light soil)	2009	89	**30**	-	Field pea	**0.4**	**1.5**	$2.09

[a]Figures in italics were un-replicated paddock-scale demonstrations.
[b]Figures in bold are statistically significant ($p<0.05$).

2.3 Conservation of nutrients

It is reasonable to assume retained stubbles will recycle the nutrients they contain in the farming system. However, stating the nutrient content of stubble as equivalent of fertiliser inputs (Early *et al.* 1997) implies a complete loss of nutrient with burning of stubble, and that the nutrient retained with stubble is highly plant available, which is not the case. Nitrogen (N) and phosphorus (P) contained in stubble are slow to recycle into a plant available form.

Conservation of nitrogen and phosphorus in stubble retained systems

Claims of loss of nutrient from stubble burning are probably exaggerated. Both recent papers (Francis 2011; Midwood *et al.* 2011) draw their data from Kirkby (2003), which in turn relied on data from Angus *et al.* (1998). The estimates in the papers above are for a wheat crop yielding 5 t/ha of grain with 7.5 t/ha of stubble. The burn conditions were described as a 'hot burn'. Under these conditions the losses of gaseous oxides (nitrogen, sulfur and carbon) were high, as in all burns, and the losses of solid oxides (calcium, potassium, phosphorus and magnesium) averaged 46% (Scott *et al.* 2010). More typical values for the loss of solid oxides were 3-11% (see Scott *et al.* 2010). Typical nutrient losses for Wagga Wagga, NSW for an autumn burn of 6.6 t/ha of stubble were estimated to be 0.5 kg P/ha, 11 kg K/ha and 6 kg S/ha. In a low rainfall setting (Condobolin, NSW) with 2.3 t/ha of stubble average losses were estimated to be 0.2 kg P/ha, 4 kg K/ha and 2 kg S/ha (Scott *et al.* 2010). The major nutrient loss was nitrogen (Wagga Wagga, 26 kg/ha; Condobolin, 9 kg/ha).

Heenan *et al*. (2004) presented total soil N for the 0-10 cm layer at Wagga Wagga NSW after 21 years of wheat-lupin rotation using no-till, where stubble was either burnt or retained. The annual rate of change of total soil nitrogen was -13 kg/ha/year (a loss of N) for retained stubble and -28 kg/ha/year for burnt stubble. The difference (15 kg/ha/year) is the result of stubble retention compared with stubble burning. As this amount of nitrogen was in the surface 0-10 cm, the estimated value of 26 kg N/ha/year lost by stubble burning seems credible. However total N declined in both stubble retained and stubble burnt systems.

The 15 kg/ha/year difference in N due to stubble retention would also be expected to include any non-symbiotic N fixation (NSNF) resulting from retained stubble (Gupta *et al.* 2011). Gupta has suggested that NSNF is possible in systems where carbon input (i.e. stubble retention) is high. In southern Australian systems Gupta *et al.* (2006) suggested the range of potential NSNF was 1-25 kg/ha/year. However, higher soil N would inhibit NSNF, as organisms involved in NSNF would utilise available soil N in preference to fixing N, as fixation was energy demanding. Gupta *et al*. (2006) identified an apparent NSNF of about 20 kg/ha/year in a 17 year experiment at Avon in SA under continuous wheat with no added N fertiliser. Similarly, Mullaly *et al.* (1967) identified about 17 kg/ha/year input of N where legumes were removed from a pasture at Walpeup (Victoria) by spraying with herbicide. Higher apparent N inputs were recorded at Longerenong, Victoria, but the spraying was not fully effective in removing legumes from the pasture. These situations were arguably atypical as the crops would have been severely N deficient, and the pasture had no input of symbiotic N.

In the long-term experiment at Wagga Wagga NSW, Bünemann *et al*. (2006) reported total soil P in the 0-20 cm depth of soil where stubble was either retained or burnt in the cultivated treatments. The total additional P accumulated after 23 years was 186 kg/ha and 180 kg/ha where stubble was retained and burnt, respectively. Estimates of P removed by crops were identical for both treatments. This difference would represent a higher phosphorus accumulation of 0.3 kg/ha/year for the stubble retained system compared with the stubble burnt treatment.

Plant availability of nitrogen and phosphorus in retained-stubble systems
While the above discussion identifies a higher reserve of N and P in the retained-stubble system compared with the burnt stubble system, it is unclear as to the amount of either N or P that is in a plant available form.

During decomposition of buried wheat stubble, immobilisation of N is common, reducing the immediate availability to crops. The field examples given by Mary *et al.* (1996) indicated immobilisation rates of 5-13 kg/ha of N immobilised with the decomposition of 1 t/ha of wheaten stubble. Immobilisation of N during stubble decomposition reduces N availability to a following crop. Fertiliser N may be required, both to meet the requirements of the growing crop and, to hasten stubble decomposition.

On a long-term experiment at Billa Billa, Queensland, lower grain protein of wheat was associated with no-till and reduced tillage systems when combined with stubble retention (Thomas *et al.* 1995). Application of 60 kg N/ha was necessary to maximise profitability in these stubble-retained systems. Similarly, Newton (2001), working at Wilby in north-eastern Victoria, concluded that increased rates of fertiliser N were necessary during early wheat growth under stubble-retained systems to ensure adequate N following immobilisation.

Smith and Sharpley (1993) labelled the stubble with ^{15}N and carried out laboratory incubations. Mineral N in the soil from the fine ground wheaten stubble (0.25 mm) was equivalent to 3 kg/ha at 14 days and 12.2 kg/ha at 168 days when stubble was soil incorporated; equivalent to 6 and 25% of the stubble nitrogen content, respectively. When stubble was applied to the surface, mineral nitrogen from stubble was less and was as low as 1.6 kg/ha by 14 days and 5.9 kg/ha by 168 days (3 and 12 % of stubble N content). Residue-sourced nitrogen from incorporated wheat stubble, and its utilisation by a subsequent crop, was followed in the field in Kansas, United States (Wagger *et al.* 1985). Between 12 and 15% of the nitrogen in the wheat stubble was mineralised in the following season. With a range of 15 to 20 kg total N/ha applied in the stubble, the amount of mineralised N over the season was approximately 2 to 3 kg/ha. This slow recycling of N was seen as a long-term benefit in stubble-retained systems. The cycling of N in Australian dryland cereal farming in no-till retained-stubble systems is poorly understood. Most studies were done with incorporated stubble, where decomposition would be expected to be more rapid, than with surface mulched or standing stubble (Amato *et al.* 1987; Cogle *et al.* 1987).

The P in stubble in the field appears to become plant available at a slow rate. Stubble in the field lost 0-7.5% of its P content with cumulative rainfall of 52 mm (Noack *et al.* 2012). This result suggests little leaching of phosphorus by water despite its apparent high solubility in the stubble in laboratory tests. It seems probable that P release from stubble will parallel the decomposition of the stubble.

Bünemann *et al*. (2006) reported resin extractible P in the 0-10 cm soil in the long-term experiment at Wagga Wagga NSW. This measure, likely to be related to plant available P, showed no significant difference due to stubble retention or burning, when measured on five occasions during 23 years.

However, P in soil in no-till retained-stubble systems is stratified with high concentrations in the surface few centimetres of soil. The effect is to make P less available to plants. It would be anticipated that the critical soil P test values would be higher in no-till systems than in the earlier cultivated systems. Some indirect evidence of this has been found in WA and the GRDC southern region. The critical Colwell P concentration was higher from 1994 to 2011, when no-till systems were common than in the earlier times when cultivation was the practice (Llewellyn and D'Emden 2009). The critical values in WA were significantly different from the earlier time period (critical value ranges do not overlap) and in the GRDC southern region there was a similar trend, but not significant (Table 8).

Table 8. The critical Colwell P soil test values and range (0-10 cm soil depth sample) and the response of wheat yield to phosphorus fertiliser in the GRDC Western and southern regions over different times (see Bell *et al.* 2013).

Time (years)	Number	Critical Colwell P (range) for 90% max grain yield	r
		GRDC western region	
1958 - 1993	231	14 (12 - 16)	0.62
1994 -2011	138	23 (20 - 26)	0.53
		GRDC southern region	
1958 - 1993	354	22 (20 - 25)	0.49
1994 -2011	156	34 (24 - 47)	0.24

It would be reasonable to conclude that no-till systems would require higher inputs of P fertiliser to attain maximum grain yield than was the case with previous cultivated systems.

2.4 Avoidance of the smoke hazard from burning

The ability to burn stubble is a final option for growers faced with the possibility of being unable to sow a crop into heavy stubble or a delayed sowing with its associated risks. Burning also provides a management option to reduce populations of herbicide-resistant weeds, some pests and some stubble borne diseases.

The annual emissions of total carbon from natural and forest fires in Australia is very large, averaged 78 Mt C/year from 1983 to 2008 (cited by Meyer *et al.* 2008) with large inter-annual variability. Savannah burning contributes 87%, with wildfires accounting for 10% and prescribed fires only 3%, respectively.

Stubble burning, smoke and particulates

Particulates in the air from smoke are a potential cause of health problems. A high concentration of particulates in the air occurs in some locations during autumn-early winter, when stubbles are burnt, and this observation is the basis of a *prima facie* case that stubble burning is a cause, or at least a major contributor, to this risk to human health. The association of particulate pollution and human health, with emphasis on regional NSW, has been reviewed (Kolbe and Gilchrist 2011).

Since the original monograph (Scott *et al.* 2010), locality specific data have become available. In NSW regional cities the particulates in the air (PM_{10}, particulate matter of < 10 µm) frequently exceed air quality standards of 50 micrograms per cubic metre ($\mu g/m^3$) (24-hour average; Figure 7) (Anon 2012a). Wagga Wagga has the greatest number of days of exceedences, with Albury also notable; both cities are in southern NSW cropping areas. Bathurst is beyond the main wheatbelt to the east, and Tamworth is located on the margin of the north-western cropping areas where burning of stubble is less common.

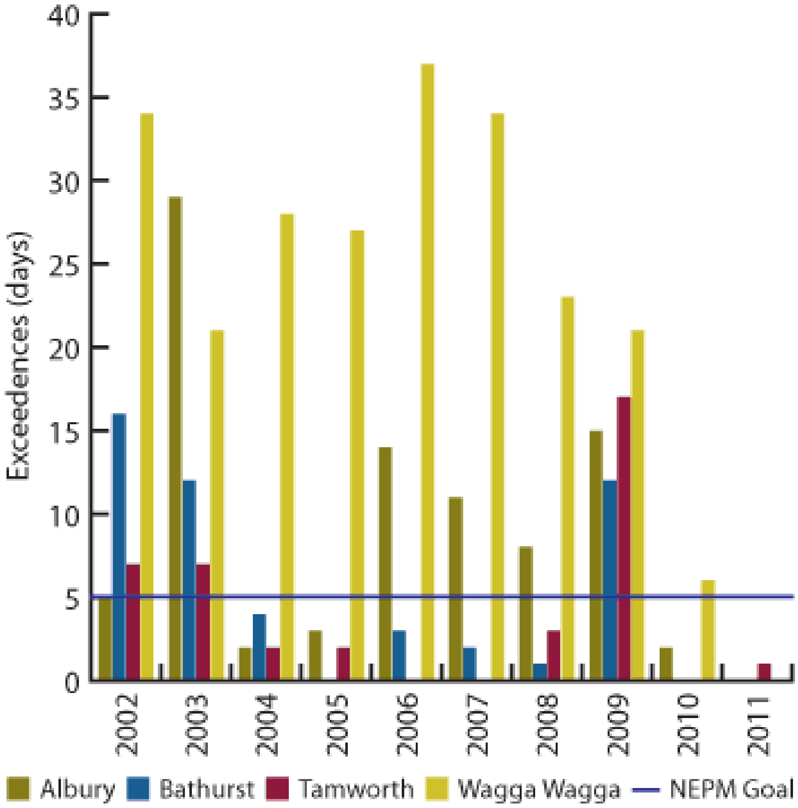

Figure 7. Exceedences of the AAQ NEPM standard for particles (PM_{10}) in New South Wales rural cities, 2002–2011 (from Anon 2012a)[9].

Hotspots, detected by satellite between 2003 and 2007, have indicated that most stubble fires in the Wagga-Albury area occur in autumn and winter (Figure 8). More specifically, burning occurred most frequently during April and May with some burning continuing into June (Figure 9) (Meyer *et al.* 2008). Similarly, the measurement of particulates in the air (PM_{10}) at Wagga Wagga during 2003 to 2007 showed a similar seasonal pattern (Figure 10). When days of known dust storms and smoke from large uncontrolled fires were excluded the pattern of autumn-winter particulate pollution was even clearer (Figure 10).

[9] © State of New South Wales through the Environment Protection Authority

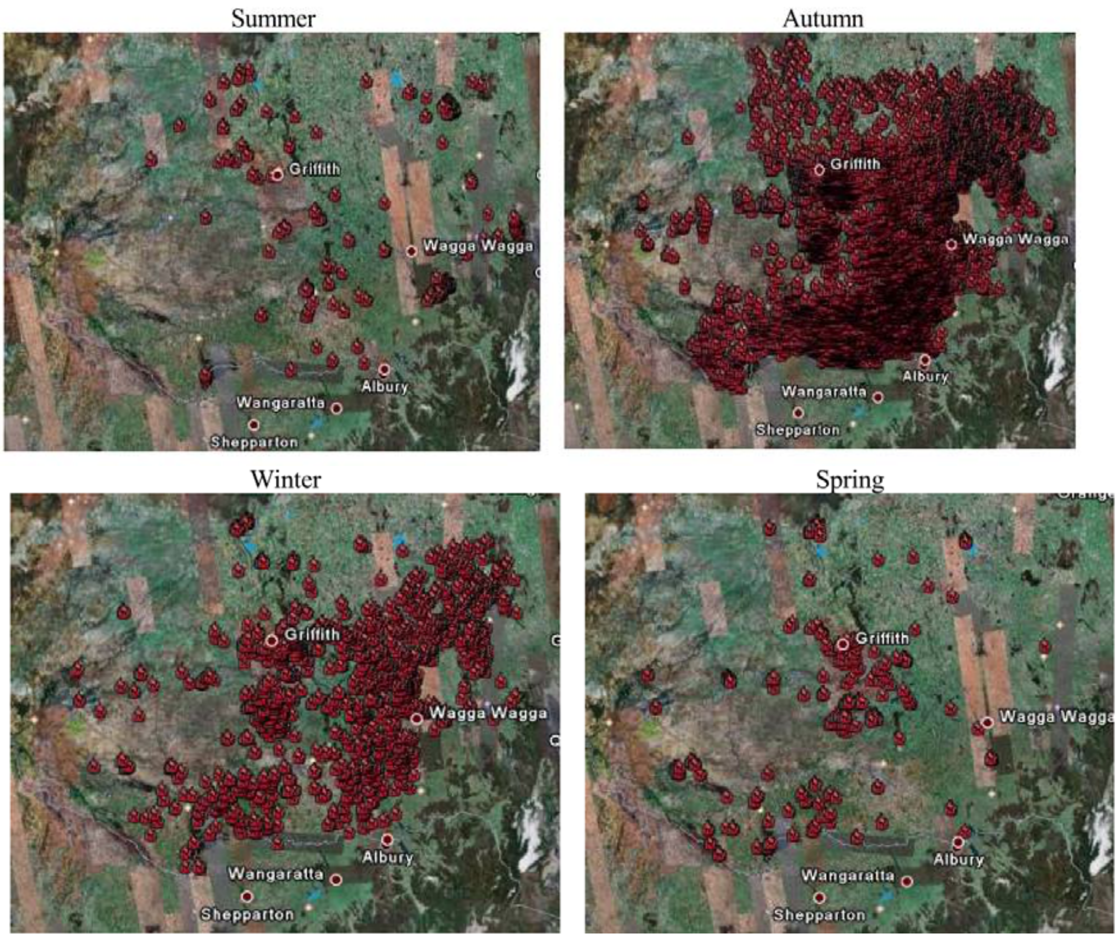

Figure 8. Hotspots identified from MODIS satellite data by season (2003-2007) (from Meyer *et al.* 2008), reprinted with permission[10].

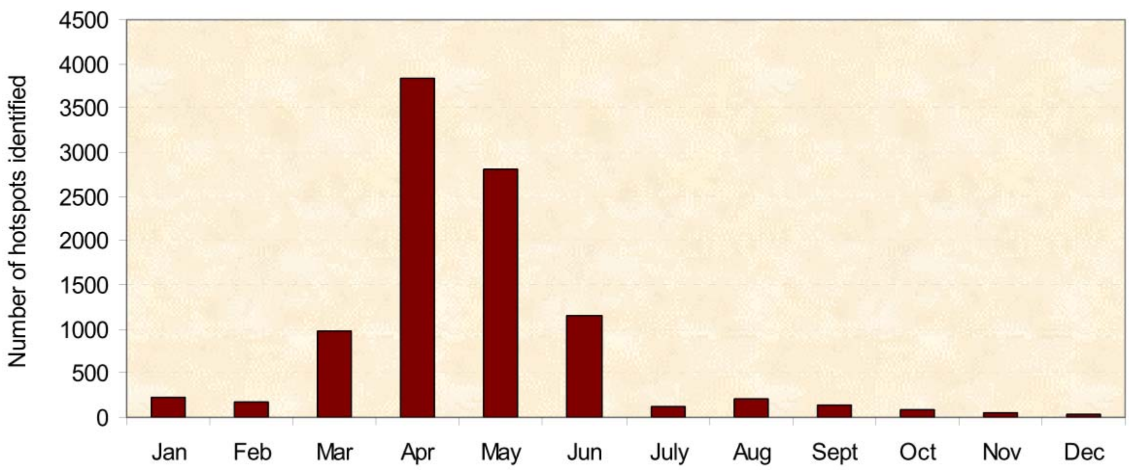

Figure 9. The distribution of hotspots identified by MODIS satellite data by month (2003-2007) (from Meyer *et al.* 2008), reprinted with permission[11]

[10] © CSIRO Environment Group, (2008), 25 October, 2013.
[11] © CSIRO Environment Group, (2008), 25 October, 2013.

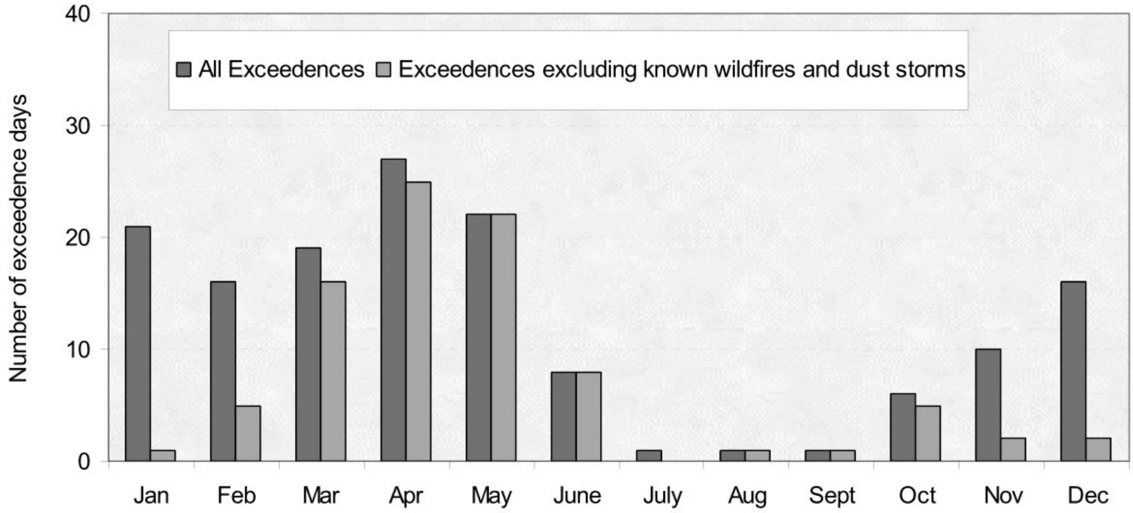

Figure 10. The number of days by month that particulates in the air (PM_{10}) exceeded the standard of 50 µg/m^3 (24-hour average) at Wagga Wagga from 2003 to 2007 (from Meyer *et al.* 2008), reprinted with permission[12].

This association of stubble burns during autumn-early winter and PM_{10} at Wagga Wagga appears to suggest that stubble burning may be the cause of the particulates in the air at that time. This has led to suggestion that legislation may be required to prevent or limit stubble burning. However, on a closer examination of the data, such a conclusion would appear to be premature.

Dust and particulates

In broad terms, very dry conditions prevailed in southern NSW from 2002 until early 2010. In these dry seasons stubble burning was limited, but extensive burning took place in the autumn of 2011 following a favourable 2010 season. It is apparent in Figure 7 that exceedences at Wagga Wagga occurred in the drier seasons (2003-2009) and there were no exceedences in 2011, a season of extensive stubble burning.

This description of burning in some seasons (2008 and 2011) can be supported by data (Kearns and Umbers 2010; Edwards *et al.* 2012). The area near Wagga Wagga and Albury (NSW/Victorian slopes) had only 2.3% of stubbles burnt during 2008 (Table 1), compared with 40.5% during 2011, yet exceedences were greater in 2008 (Figure 7).

The low rate of stubble burning during 2008 may explain the chemical characteristics of the particulates. Laevoglucosan and nss K+ concentrations were measured on the PM_{10} collected at Wagga Wagga between December 2007 and July 2008 (Figure 11)(Meyer *et al.* 2008). From December to April the PM_{10} and nss K+ concentrations followed the same trend with laevoglucan concentration low. This suggested dust as the source of particulates. Into April 2008 laevoglucans rose indicating that smoke from cellulose burning started to contribute to particulates. This trend would be consistent with wood heaters being used and/or stubble fires. While fires were recorded by satellite around Wagga Wagga (Meyer *et al.* 2008), the GRDC survey (Table 1) suggested little stubble burning during autumn of 2008. If the GRDC survey is accepted it can be argued that the elevated laevoglucans were the result of wood

[12] © CSIRO Environment Group, (2008), 25 October, 2013.

heaters being used in the city of Wagga Wagga. The absence of exceedences in 2011 (Figure 7), when stubble burning was extensive (Table 1) weakens the case for stubble burning as the cause of elevated PM_{10} during autumn/early winter.

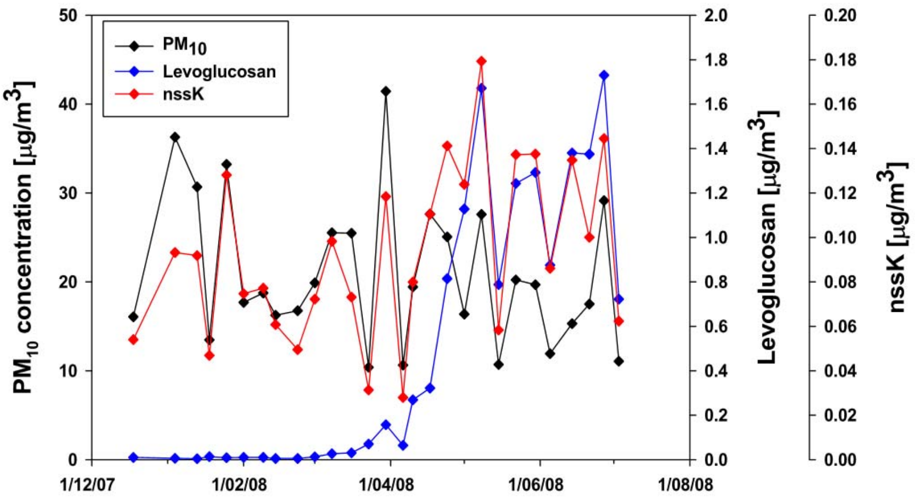

Figure 11. Weekly concentrations of PM_{10}, laevoglucosan and nssK+ measured at Wagga Wagga, New South Wales during 2008 (from Meyer *et al.* 2008), reprinted with permission[13]

The exceedences at Wagga during 2002-2009 were probably due, in large measure, to dust resulting from dry conditions. The exceedences during autumn were probably a result of this being the time of the year with minimal groundcover and risk of dust. Wagga Wagga has been more prone to dust storms than Albury (McTainsh *et al.* 1990), and this may explain the greater number of exceedences in Wagga Wagga compared with Albury. However, the contribution of stubble burning to particulates in the air remains undefined, but recognised as probably less important than previously thought.

2.5 Soil organic carbon (SOC) accumulation

While stubble retention is well recognised for its ability to protect soils against wind and water erosion, its ability to increase soil organic carbon (SOC) levels has generally been slow to negligible in Australian no-till cropping systems. This reality has been confused by the increases in SOC% in higher rainfall environments, and by the frequent use of simulation modelling (for example, RothC model, developed at Rothamsted in the United Kingdom).

Modelling of SOC

Projections over 25 years using the RothC model for Dunkeld in Victoria (Figure 12) indicated that at stubble loads of < 5t/ha, SOC% declined (Riffkin and Robertson 2010). Mulching or grazing of retained stubble increased SOC% at larger stubble loads. In further modelling the initial SOC quantity was varied from the original estimate of 70 t/ha in the 0-30 cm to 35, 59 and 95 t/ha. With continuous wheat for 25 years using a 5 t/ha stubble load at an initial 35 t/ha of SOC the model indicated that SOC was stable (+6 kg/ha/yr of SOC) where stubble was burnt, and a gain of SOC with mulched stubble (+650 kg/ha/yr). At an initial SOC of 59 t/ha stubble burning decreased SOC by 22 kg/ha/yr and stubble mulching

[13] © CSIRO Environment Group, (2008), 25 October, 2013.

increased SOC by 370 kg/ha/yr. Similar modelling was undertaken by Clough *et al.* (2010) where APSIM v6 was used to estimated stubble loads as inputs to the model. The output for 5 sites are available at http://www.sfs.org.au/research-publications_HRZfactsheets.

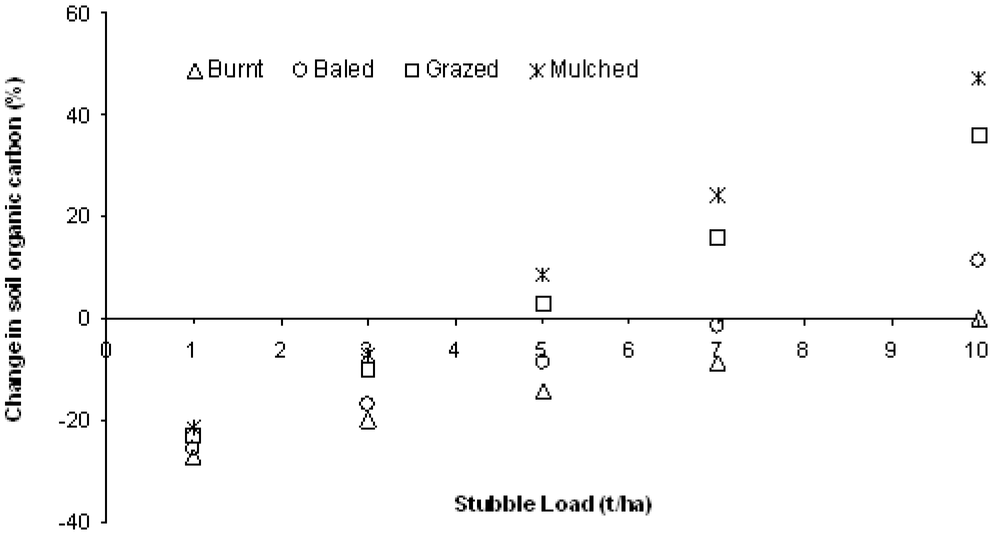

Figure 12. Modelled soil organic carbon accumulation or loss after 25 years at Dunkeld, Victoria with different stubble management regimes (from Riffkin and Robertson 2010), reprinted with permission[14].

Much of this modelling research is presented by Robertson and Nash (2013). They conclude that there is 'limited potential' for carbon accumulation in the cropping areas of Victoria.

At Wagga Wagga (initial SOC in the surface 0-30 cm layer estimated at 43 t/ha), the RothC model was used to compare the simulations of SOC (0-30 cm) using actual inputs of stubble as measured on the site at harvest, to the observed changes in SOC (Figure 13). Over 26 years (1979-2004) the RothC model over-estimated the increase in SOC with stubble retention, and slightly under-estimated the SOC where stubble was burnt. Inverse analysis showed a better fit if only 26% of the retained stubble was entered into the model rather than the entire stubble load. This result has raised the question of why we are not storing more carbon through stubble retention. The suggestions are that the carbon input is low (Chan *et al.* 2003) and/or that other nutritional effects like low N, P or Sulfur (S) are at play (Kirkby *et al.* 2011a; Kirkby *et al.* 2011b). However, the weakness of the RothC model in semi-arid environments has also been recognised and the model has been modified (Farina *et al.* 2013). The accumulation of SOC in the research of Riffkin and Robertson (2010) for retained stubble is likely to be over-estimated.

[14] © Australian Society of Agronomy (2010), 8 October, 2013.

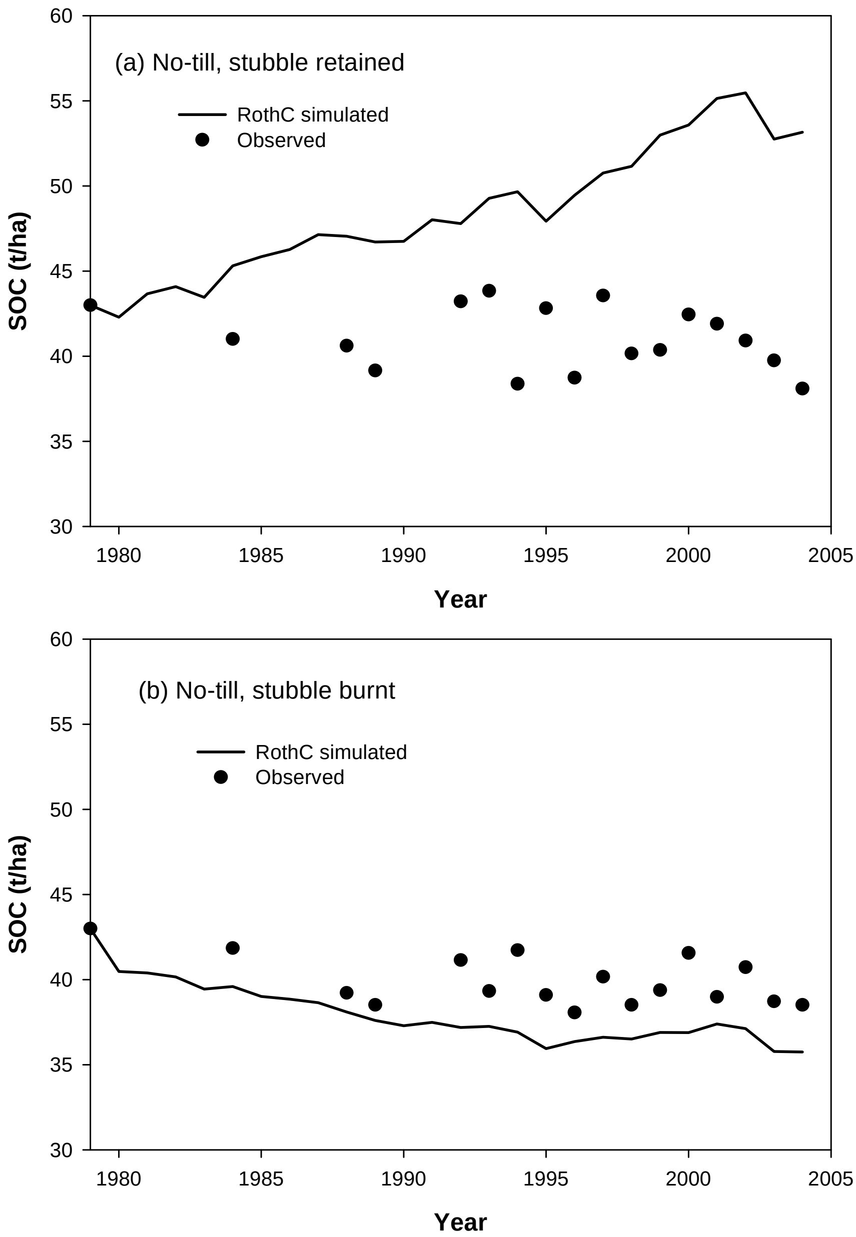

Figure 13. Comparison between the simulated (RothC) and observed organic carbon content of soils (0–30 cm) from a long-term rotation, tillage and stubble management experiment with a wheat/lupin rotation at Wagga Wagga (known as SATWAGL). Stubble was either (a) retained or (b) burnt during autumn (from Liu *et al.* 2009), reprinted with permission[15].

The RothC model is recognised to poorly match data from semi-arid environments (Farina *et al.* 2013). A semi-arid environment was defined by (Farina *et al.* 2013) as an environment of < 600 mm annual average rainfall where the ratio of precipitation/potential evapotranspiration was < 0.65. This would include all areas in the GRDC southern region with < 600 mm rainfall. The data used to evaluate the reparameterised model by Farina *et al.* (2013) were from Foggia (Italy), Cordoba and Zaragosa (Spain), Tel Hadya (Syria) and the Waite Institute (Australia).

[15] ©Elsevier (2009), 15 October, 2013.

Field measurement of SOC

The general observation of low or ineffective storage of carbon with conservation farming (no tillage and stubble retention) is common in Australia. No-till and stubble retention, compared with cultivation and stubble burning has little effect on soil organic carbon in Australian temperate cropping areas, at least when average annual rainfall was about 500 mm or less (Chan *et al.* 2003). The suggestion was that a low production of biomass may be a barrier to increasing SOC. At a site at Wagga Wagga NSW, where conservation farming maintained higher SOC% in the 0-10 cm soil depth elimination of tillage was the major effect with stubble retention contributing 23% of the difference (Chan and Heenan 2004). It has been estimated that only 4% of the carbon in the stubble was retained in the SOC (Haines and Uren 1990).

Conyers *et al.* (2012) revisited two long-term experiments, one at Wagga Wagga NSW, and the other at Rutherglen Victoria. The Wagga Wagga experiment had a wheat/lupin rotation with stubble retained or burnt every year either with or without cultivation. At Rutherglen the rotation was wheat-grain legume, where the grain legume was either lupins or faba beans. The same treatments were imposed except for the cultivated treatment with retained stubble. The experiments had been operating for 25 years (Wagga Wagga) or 28 years (Rutherglen) at the time of soil sampling.

At Wagga Wagga the only statistically significant difference in C% (measured by LECO) was between the cultivated and direct drilled treatments in the 0-5m layer (Figure 14). There was no significant difference at any soil depth in the direct drilled treatments whether stubble was burnt or retained. Similarly, in the cultivated treatments there were no significant differences at any soil depth between burnt or retained stubble. However, there was a trend in the 0-5 cm layer of soil for the retained-stubble treatments to have a slightly higher C% than the treatments with burnt stubble. In the Rutherglen data there were no statistically significant differences between treatments at any depth, although the treatment with direct drilled, burnt stubble tended to be higher in C% than the cultivated treatment with stubble burnt ($P = 0.06$).

Australian data on the effect of stubble retention has been reviewed by Lam *et al.* (2013) using meta-analysis. They concluded that SOC was about 10% greater where stubble was retained compared with removed or burnt, and this effect reduced from a maximum in the category < 10 years duration but was nil in the categories spanning 21-30 years. That is, there was a trend for the advantage to be established in the early phase of experiments or experiments of short duration, but that this advantage could not be demonstrated in longer term experiments. It should be noted that Lam *et al.* (2013) compared stubble retention with stubble removal and that the 'increase' is based on that comparison. In a number of the long-term experiments the reality was that SOC declined with both stubble removal and retention (for example, Chan *et al.* 2011; Dalal *et al.* 2011). The decline was greatest with removed stubble. Chan *et al.* (2011) reported that in a no-till system at Wagga Wagga SOC declined by 52 kg/ha/year when stubble was retained, and was lost at 98 kg/ha/year where stubble was burnt. These loss rates were not statistically different from one another, and not different from zero.

While the cumulative effects of SOC% change from stubble retention compared to stubble burning remains difficult to measure, it follows that occasional stubble burning will not have a measurable impact on the accumulation of SOC.

Recent research by CSIRO has shown the slow to negligible increases in carbon levels may be due to low availability of N, P and S, which are required in relatively constant ratios to stabilise SOC (Kirkby *et al.* 2011a; Kirkby *et al.* 2011b). In no-till farming systems, efficient fertiliser inputs mean stubbles are generally low in N, P and S and stubbles are retained at the soil surface. This organic matter is unable to adequately provide the nutrients required to increase SOC. However, research has also shown that incorporating stubbles and applying sufficient fertiliser (particularly P and S) can increase the levels of stable organic carbon in the soil. As with lime incorporation, this approach requires a level of soil disturbance that may not be acceptable to no-till farmers. Furthermore, the cost of the nutrient additions required to sequester one t/ha of carbon were estimated to cost about $250 (Kirkby *et al.* 2011a).

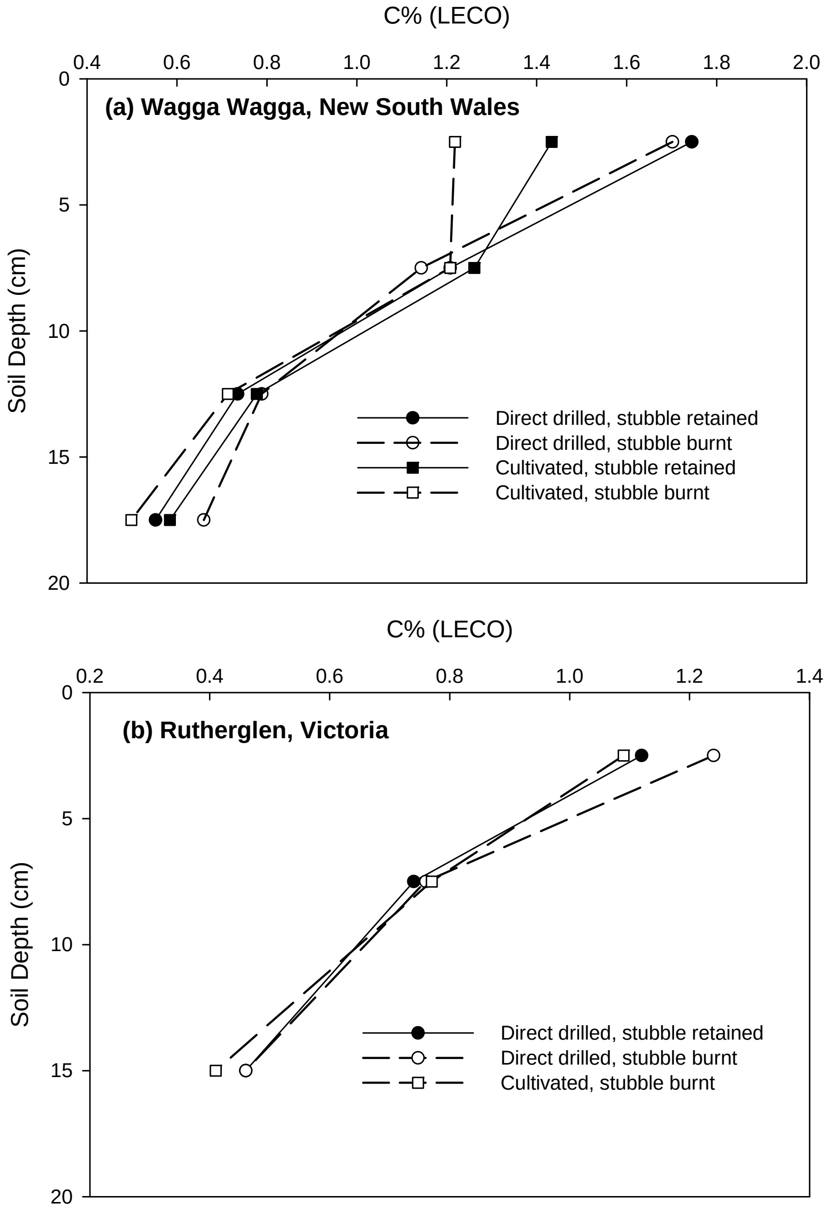

Figure 14. Soil carbon in the profile of (a) the SATWAGL experiment at Wagga Wagga, New South Wales after 25 years and (b) the SR1 experiment at Rutherglen after 28 years (after Conyers *et al.* 2012).

3. CONCERNS WITH STUBBLE RETENTION

3.1 Sowing machinery

Setting up sowing machinery
Many studies and surveys have cited machinery blockage at sowing as a major impediment to the adoption full stubble retention (Vanclay and Glyde 1994; Koen 2005). Due to the high capital cost of new equipment many growers have modified their existing sowing equipment to handle greater volumes of stubble by increasing row spacing and altering tine configuration to allow more space for stubble to flow through.

Mead and Qaisrani (2003) found that the following list of guidelines would help avoid problems when buying or modifying machinery:-

- The vertical clearance and the rank spacing should be at least 50 cm.
- The tine layout should be a minimum of five ranks, allowing tines to be one row space and two ranks apart or vice versa.
- A curved shape on the leading edge of the tine is best with a diameter of 4 to 8 cm, and flat-on tines are better than edge-on.
- A shank angle, vertical or tilted backwards with a high 'C' shape above the stubble flow, will work best.
- The drawbar should be long enough to add an extra rank at the front, so the turning radius is not compromised.
- Wheel positioning can also affect the tine mounting as blockages can occur if the residues flow onto the wheel.
- Wheels mounted outside the frame will give greater flexibility for changing position of tines.
- If the seeder is too long it can compromise precision depth placement. An alternative is to increase row spacing, which will reduce tine and point numbers, but may affect crop yield. A press wheel to control sowing depth may have advantages here as well.
- Well-designed machinery, with no catch points, is less likely to cause residue stoppages.
- Recessed bolt heads and the use of knife points will streamline trash flow.
- Operating the equipment at shallower depth and lower speed gives less clumping and soil throw and allows smooth operation without stoppages.
- Tine shank add-ons, including Pig's Tails® or other plastic/metal guards, improve trash flow around the tine. Alternatively, tread wheel residue managers hold down the stubble beside the shank as it moves through.

Disc seeders
An alternative to modifying tine machines is to use disc seeders and coulters that increase the capability for handling heavy stubble loads, minimise soil disturbance and reduce draft requirements, but they are not without their problems. The initial cost and on-going maintenance, use in wet or rocky conditions, compaction, 'hair pinning' and seed and fertiliser placement issues all need investigation before this technology will be accepted in many areas.

The adoption of zero-till systems using disc seeders is rapidly increasing in some areas, particularly with continuous cropping systems as it enables minimal soil disturbance and retention of greater amounts of stubble, particularly at narrow row spacings. Although improvements in soil structure and infiltration rates have been clearly demonstrated, these benefits take time and growers need to be aware of limitations during the transition from a tine system (Haskins and Condon 2012).

Disc seeders work best in standing stubble (inter-row sowing) or where residue has been spread evenly across the header width using straw choppers or spreaders to minimise hair-pinning. Hair-pinning occurs when straw is bent into the furrow instead of cut through by the discs, affecting the seed/soil contact and sowing depth. Residue managers such as Aricks® wheels can improve crop establishment by clearing stubble ahead of the disc openers. However, growers need to take care to avoid crop damage from herbicide concentrated in the cleared stubble area (Ashworth *et al.* 2010; Condon 2013). Due to the potential for crop damage many pre-emergent herbicide labels do not currently support use with disc seeders, although research and development into this issue is continuing (Desbiolles 2005; Kleemann and Boutsalis 2008). Desbiolles (2004) found in a long-term sowing system trial at Minlaton in SA that seed placement with some disc systems resulted in poor crop establishment, trifluralin phytotoxicity and lowest grain yields compared with the tine systems when at low speed. Walsh *et al.* (2009) found knife points consistently maximised wheat seedling establishment, which translated to higher biomass at anthesis but not significantly to grain yield differences when compared with disc systems. The reductions in emergence from the disc system were due to stubble pinning and herbicide damage.

Replicated trials in SA and NSW from 2004-2006 showed that inter-row sowing into standing stubble in a no-till retained-stubble system was the highest yielding treatment compared with both burnt and slashed stubble sown on the previous row. Yield increases of 6-9% can be expected for wheat-on-wheat rotations with inter-row sowing. While there was no yield advantage with inter-row sown lentils, standing stubble provided support for the plants, which gave improved harvestability. This improvement is significant as the increase in harvest speed allows greater areas of lentils to be grown in the system at high gross margins (McCallum 2005).

Inter-row sowing is not always easy to implement successfully as many growers have found over the past few wet seasons (since 2010). The use of 2 cm accuracy GPS guidance (2 cm real time kinetics (RTK) with a base station) is required. Sowing in the same direction each year is recommended as sowing rigs will 'crab' on sloping paddocks, but hopefully in the same pattern each year (McCallum 2004). Other problems have been seen in southern NSW with large stubble loads (>10 t/ha) where stubbles have rotted off at the base during wet summers, causing blockages when inter-row sowing (Burns *et al.* 2013).

Trials at the Birchip Cropping Group (BCG) site during 2006 showed that inter-row sowing reduced straw burial (Browne and Jones 2008b). BCG trials during 2009 in the Wimmera-Mallee region of Victoria (Browne 2009) showed that time of sowing was more important than the sowing system itself, but the poor depth control in disc systems can cause problems and in these trials the knife point systems out-yielded the disc system (Table 9).

Several grower groups are carrying out research on disc versus tine sowing. The Riverine Plains group has used replicated trials as part of the Water Use Efficiency project that has been done over the period 2009-2013 (Poole and Poole *et al*. references; see Table 9). The experiments included row space studies. In Table 9 the data given are the mean over the different row spacings. Results show there are few significant differences between the disc and tine systems for wheat sown into mulched stubbles of wheat, canola and faba beans, although plant establishment tended to be equal or better for the disc system (Table 9). The tine system gave greater establishment density for canola during the 2012 season.

Table 9. Comparisons for plant establishment and yield in wheat and canola of disc and tine sowing implements in Victoria and southern New South Wales.

		Establishment (plants/m^2)			Yield (t/ha)		
Site (year; stubble)	Reference	Disc	Tine	LSD 5%	Disc	Tine	LSD 5%
				Wheat sowings			
Woomelang[a] (2009; na[b])	Browne (2009)	93	114	ns[c]	2.44	2.60	na
St Arnaud[a] (2009; na)	Browne (2009)	102	134	12	1.79	2.06	na
Coreen (2009;canola)	Poole (2010c)	167	158	ns	2.64	2.45	0.12
Bungeet(2009; wheat)	Poole (2010b)	154	139	27	2.86	2.85	ns
Coreen (2010; canola)	Poole *et al.* (2011c)	138	114	10	6.18	5.95	ns
Coreen (2010; wheat)	Poole *et al.* (2011b)	134	121	9	4.91	4.90	ns
Bungeet (2010; faba bean)	Poole *et al.* (2011d)	216	220	ns	5.05	5.08	ns
Coreen (2011; wheat)	Poole *et al.* (2012b)	142	138	ns	3.27	2.90	0.29
Bungeet (2011; canola)	Poole *et al.* (2012d)	111	111	ns	3.48	3.87	0.27
Bungeet (2011; wheat)	Poole *et al.* (2012c)	116	114	ns	3.85	3.86	ns
Coreen (2012; canola)	Poole *et al.* (2013c)	169	171	ns	2.90	2.94	ns
				Canola sowings			
Coreen (2009; triticale)	Poole (2010a)	58	49	5	1.63	1.54	0.09
Coreen (2011; wheat)	Poole *et al.* (2012a)	29	30	ns	2.10	2.06	ns
Bungeet (2012; wheat)	Poole *et al.* (2013a)	163	190	11	2.65	2.53	0.10
Coreen (2012; wheat)	Poole *et al.* (2013b)	192	236	21	2.13	2.08	ns

[a]early sowing only; no reference to stubble present; [b]not available; [c]not significant

Ensuring uniform straw distribution through the use of appropriate spreaders, choppers or even stripper fronts, is a critical step in managing stubble, particularly when using disc seeders. Many standard straw choppers and spreaders tend to concentrate chaff and straw directly behind the header, reducing crop establishment and herbicide efficacy. The residue spreading pattern has been improved on many of the newer model headers, and several units can also be retro-fitted to older models (for example, MAV® straw chopper or PowerCast® tailboard). Despite these improvements straw spreaders are currently only able to spread residue evenly in all conditions across the width of a 9 m or 10.5 m front (30-35 ft). Spreading across wider fronts (12 m or 13.5 m) can be improved by increasing the straw cutting height to reduce the amount of residue to be moved, and by adjusting rotor speed and vane settings in the paddock to suit windy conditions or sloping paddocks (Condon 2013).

3.2 Row spacing and retained stubble

Widening of row spacing is a management, and subsequent machinery modification, to assist the passage of sowing equipment through heavy stubble loads. The 'traditional' row spacing of 18 cm has been gradually widened with the adoption of stubble retention. This widening of row spacing has been seen as the cost paid for retaining stubble, as widening of rows generally decreases the yield of cereals (Scott *et al.* 2010). This topic has been further explored for Australia by Scott *et al*. (2013). The major relationships from Scott *et al.* (2013) is presented in Figure 15. These figures have been overlain with data from Poole (2010b, 2010c), Poole *et al*. (2011d, 2011b, 2011c, 2012c, 2012d, 2012b; 2013c), Hancock (2005, 2006), Hancock *et al.* (2007), Hancock and Frischke (2008) Frischke (2008) and Frischke *et al.* (2006) for wheat, and Poole (2010a) and Poole *et al*. (2012a, 2013a, 2013b) for canola.

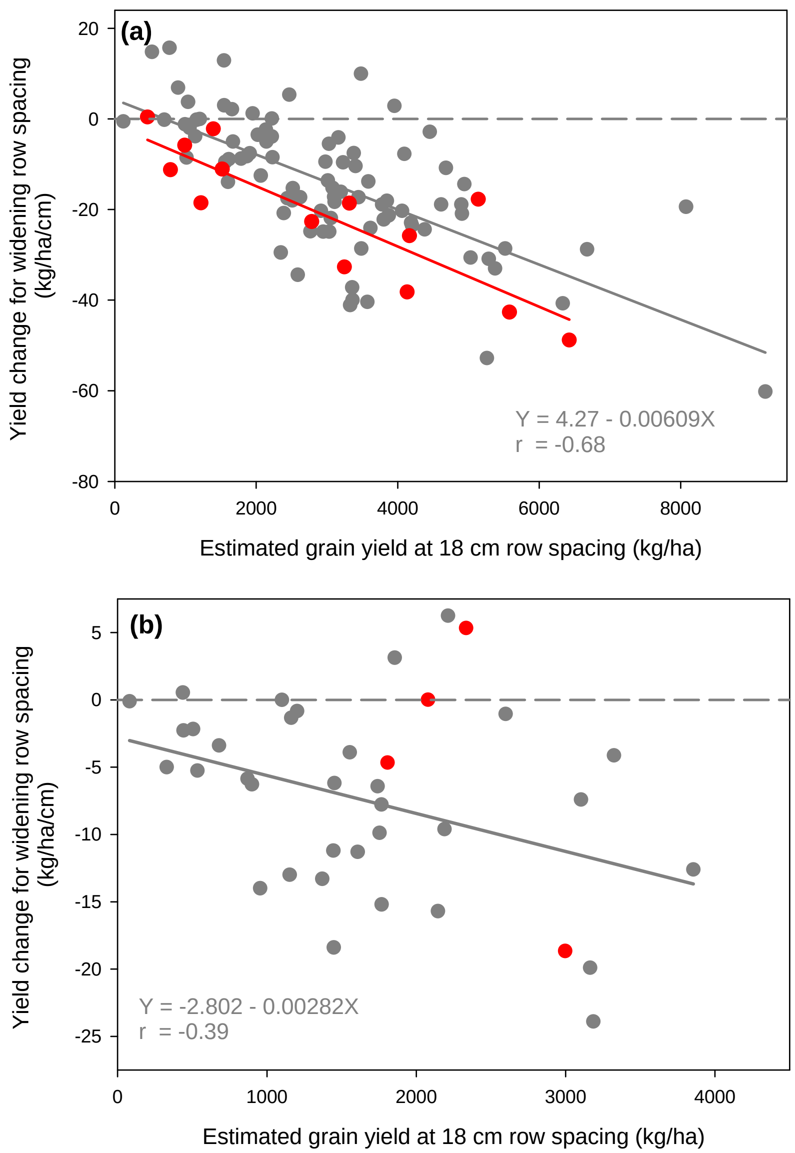

Figure 15. Yield change from widening rows from Scott et al. (2013) for (a) wheat and (b) canola in grey, overlain with data from Riverine Plains and Eyre Peninsula Farming Systems groups (in red; see text for details).

The re-analysis of all data resulted in a modification of the relationships given in Figure 15. The resulting relationships were:-

Wheat

Yield loss (kg/ha/cm) = 3.41 - 0.00613 (yield at 18 cm; kg/ha)
n= 103
r = -0.70

Canola

Yield loss (kg/ha/cm) = -2.802 - 0.00282 (yield at 18 cm; kg/ha)
n= 38
r = -0.35

Using these relationships, a general description of the yield loss can be constructed as a 'lookup' table (Table 10). At higher grain yields of wheat and wider row spacings it is clear the yield losses can be substantial; at 4 t/ha in 18 cm rows, doubling row spacing to 36 cm decreased yield by 9.5%. With canola yield of 2.5 t/ha at 18 cm row spacing, doubling row spacing to 36 cm decreased yields by 7%.

Table 10. The yield of wheat and canola at 18 cm row spacing and at various row spacings with yield derived from the equations above.

	Estimated yields (kg/ha) at various row spacings		
Yield at 18 cm	27 cm	36 cm	45 cm
Wheat			
500	503	506	509
1000	976	951	927
1500	1448	1396	1344
2000	1920	1841	1761
3000	2865	2730	2596
4000	3810	3620	3430
5000	4755	4510	4265
6000	5700	5399	5099
7000	6645	6289	5934
Canola			
500	462	424	386
1000	949	899	848
1500	1437	1373	1310
2000	1924	1848	1772
2500	2411	2323	2234
3000	2899	2797	2696
3500	3386	3272	3158
4000	3873	3747	3620

3.3 Inter-row sowing and retained stubble

The adoption of inter-row sowing is another recent innovation aimed at handling heavy stubbles. A new crop is sown between the rows of standing stubble of the previous crop. The sowing tines or discs are clear of stubble and, if the tine and frame height are adequate and/or the original stubble was cut short, the sowing machinery can pass through the standing stubble making limited or no contact with the stubble. Such systems seem to require a row spacing of about 30 cm to make this possible, although a row spacing of 22.5 cm has been considered adequate (Anon undated-b). Major issues include the reliable handling of heavy stubbles using inter-row sowing, and the type of equipment and capital cost required to achieve successful inter-row sowing.

Inter-row sowing is similar to wide-row sowing, except the stubble between the rows is standing stubble, where in previous systems of stubble retention it was either incorporated, slashed or simply sown through, and so the arrangement of stubble varied. The arrangement of rows of newly-sown crop between rows of the previous year's standing stubble present some unique options and issues.

Inter-row sowing and machinery

Inter-row sowing requires '2 cm' GPS guidance with auto steer on the tractor (for example, McCallum 2004). Guidance systems with two centimetre accuracy are often referred to as Real Time Kinetic (RTK) systems and require a base station to maintain a highly accurate and repeatable GPS positioning (Knight undated). However, a trailed implement can be displaced sideways by irregularities in the ground, uneven depth of ground engaging parts or by travelling across a slope or around a curve. The implement will realign after irregular displacements assisted by tyres and/or ground-engaging guidance discs. Implement guidance systems also overcome these problems. They can use GPS information or camera mounted systems which recognise crop, stubble or soil furrow and engage steering software to correct implement positioning via steerable wheel, ground engaging discs or a hydraulic side-moving hitch point (see Thacker and Coates 2002; Butler and Desbiolles 2008).

Reduced stubble load with inter-row sowing

The use of row widths of 30 cm rather than (say) 18 cm will reduce the amount of stubble present, as well as grain yield (Table 11). Estimates in heavy stubble can be made from the data of Poole and Poole *et al* in southern NSW and north-eastern Victoria (see Table 11).

Table 11. Estimated amount of stubble (kg/ha) remaining at harvest from 18 cm and 30 cm row spaced wheat crops at Coreen (southern New South Wales) and Bungeet (north-eastern Victoria).

Site (year)	Previous crop stubble	Stubble at 18 cm row space (kg/ha)	Stubble at 30 cm row space (kg/ha)	Loss in stubble (18 to 30 cm rows) (kg/ha)	Reference
Bungeet (2009)	wheat	8252	6130	2122	Poole (2010b)
Coreen (2009)	canola	6224	5647	577	Poole (2010c)
Coreen (2010)	wheat	10422	9149	1273	Poole *et al.* (2011b)
Coreen (2010)	canola	10604	9539	1066	Poole *et al.* (2011c)
Coreen (2011)	wheat	6890	6886	3	Poole *et al.* (2012b)
Bungeet (2011)	wheat	12450	8587	3863	Poole *et al.* (2012c)
Bungeet (2011)	canola	8901	7836	1065	Poole *et al.* (2012d)

Inter-row sowing and soil borne disease

The physical separation of the new seedlings of wheat from the old crowns of the previous wheat crop can reduce the infection rate of crown rot caused by the fungus *Fusarium* *pseudograminearum* and common root rot caused by *Bipolaris sorokiniana* (Simpfendorfer *et al*. 2004; Simpfendorfer *et al*. 2006a). The value of inter-row sowing is that it reduces the rate of inoculum build-up in a paddock. However, inter-row sowing is not a comprehensive answer for control of crown rot, but a useful component of an integrated disease management system. The location of the new crop of wheat in the inter-row in the presence of crown rot seems to offer a yield advantage over sowing into the previous rows (Table 12a). However it is apparent that this advantage appears to persist in the presence of take-all, and also in situations of no apparent disease (Table 12b).

Inter-row sowing may need to be compared with a sowing arrangement in which the old row location is disregarded, rather than a comparison of inter-row with in-row sowing. This has been achieved in Canada (Coles 2011) by comparing inter-row sowing with sowing across the rows of the previous crop.

Table 12. Yield advantage of sowing inter-row compared with in-row sowing (a) when crown rot was present and (b) in the absence of crown rot.

Site	Row sowing	Yield (t/ha)	Disease present	Comment	Reference
			(a) Crown rot		
Tamworth NSW 2004	Inter-row In-row	2.52 2.30 LSD 5%=na	Crown rot	Single site	Verrell *et al*. (2005)
Northern NSW 2006	Inter-row In-row	2.12 2.02 LSD 5%=na	Crown rot	7 sites	Daniel and Simpfendorfer (2007)
			(b) other		
Sandilands SA 2004	Inter-row In-row	4.11 3.88 LSD 5%=0.21	Take all	Single site	McCallum (2005)
Sandilands SA 2005	Inter-row In-row	3.74 3.42 LSD 5%=0.31	Take all and CCN[a]	Single site	McCallum (2005)
Hart SA 2005	Inter-row In-row	2.99 2.77 LSD 5%=0.13	None	Single site	McCallum (2005)
Buckleboo SA 2005	Inter-row In-row	2.82 2.79 LSD 5%=ns	None	Single site	McCallum (2005)
Kimba SA (2006)	Inter-row In-row	0.25 0.17 LSD 5%=0.06	None	Single site	McCallum (2006)
Waikerie SA (2006)	Inter-row In-row	0.83 0.70 LSD 5%=ns	None	Single site	McCallum (2006)

[a]Cereal Cyst Nematode

Finally, in simple rotations (for example, wheat-canola), the wheat and canola rows would be placed on the previous wheat or canola rows in a third season. These effects can potentially aid disease carry over (such as with crown rot and blackleg). Verrell (2013) recommends sowing wheat on the break crop row and sowing the subsequent break crop on the wheat crop inter-row. This way the wheat and break crops are sown in the same location in (say) year one and four of the rotation, so extending the time for breakdown of any stubble and crowns potentially carrying disease. This approach may only be possible with some break crops (for example, chickpeas) where the stubble is not a barrier to re-sowing in-row.

Herbicide application and inter-row sowing

Foliar or soil-applied herbicides can strike stubble, which potentially interferes with the herbicide's ability to make contact with weeds or the soil surface. With flattened or mulched stubble a portion of the herbicide can lodge in the stubble, and then leach or volatilise from the stubble (Banks and Robinson 1982; Petersen and Shea 1985; Dao 1991; Wolf *et al.* 2000). The effects of standing stubble in the inter-row of a new crop, rather than continuous standing stubble or flattened stubble, are unclear. However, Condon (2013) suggests that matching the spray nozzle spacing to the row spacing, and placing the nozzle of the sprayer directly over the middle of the inter-row space, could result in less interference from the stubble and permit a higher proportion of the spray to reach the soil surface of the inter-row for soil-applied herbicides, or to reach weeds in the inter-row space. Further, higher water volumes (>80 L/ha) and larger, non-air inducted nozzles also allow more herbicide to reach the soil (Condon 2013).

Herbicide carry over effects in inter-row cropping may limit the choice of second crop after the application of some herbicides to the first crop. This may occur where higher rates of herbicide were applied, and/or where soil throw has accumulated any potential herbicide carry over into the inter-row space. Sulfonyl ureas (for example, Glean®, Logran®) can be carried over in this way and damage new sown pulse crops (Haskins 2012).

Standing stubble and 'trellising'

The presence of standing cereal stubble in the inter-row has been claimed to improve the yield of some pulse crops either directly or through improved crop height and harvestability (Brand 2009). This improved crop height is claimed to be due to a ‘trellising’ effect with crops such as lentils (McCallum 2006; Brand 2009) and peas (EL Armstong pers comm.) (Table 13). In no-till systems the standing stubble could be expected to be only about 30 cm or less in height, but it has been implied this still contributes to improved harvestability.

Table 13. The height of the plants and the first pod of lentils inter-row sown into wheat stubble (3 t/ha) either burnt, slashed or standing (from McCallum 2006), reprinted with permission[16].

Stubble treatment	Plant height (cm)	Height to first pod (cm)
Burnt	23.8	14.6
Slashed	25.7	16.1
Standing	31.4	20.2
LSD	3.3	1.1

Inter-row sowing and foliar disease spread

The open canopy in wide row sowings, with higher wind speed and lower humidity, has been claimed to provide a less disease prone environment than in crops with narrow row spacing

[16] Yorke Peninsula Alkaline Soils Group (2006), 27 October, 2013.

(Peltzer *et al.* 2009). However, the presence of standing stubble in the inter-row of crops could be expected to reduce air flow and negate the 'open crop' effect.

Residual fertiliser and inter-row sowing
With inter-row sowing the residual fertiliser band from a previous crop is located remotely from the seed placement of the new crop, limiting the contribution of residual fertiliser to crop nutrition. With fertiliser banded in widely spaced rows it is difficult to achieve representative soil sampling before sowing the second crop. The question remains as to whether the soil sample should be random, presumably to include the previous fertiliser band, or taken only in the stubble inter-row space; the site of the new crop row. Substantial differences in the residual fertiliser phosphorus have been demonstrated between sowing into the previous row or between rows (inter-row sown) with no added fertiliser in the second crop. The effects were less pronounced with narrow row sown crops (Fettell 2010) (Figure 16). However, when fertiliser phosphorus was applied in 2009, the effects were much smaller (Fettell 2010).

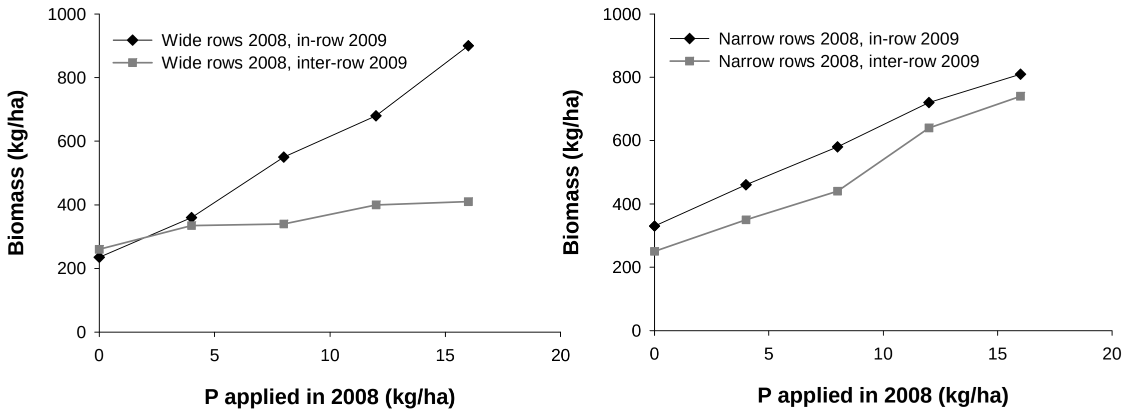

Figure 16. Early biomass in wheat during 2009 in response to residual phosphorus from fertiliser applied in 2008 either in-row or inter-row with narrow rows (17 cm) or wide rows (mean of 30 and 43 cm row spacing) when sown without fertiliser during 2009 (from Fettell 2010), reprinted with permission[17].

3.4 Animal production and retained stubble

Crop stubbles are widely considered a valuable feed source for livestock. Grazing stubble has other benefits beyond those for livestock, including reducing high stubble loads prior to sowing, utilisation of grain remaining after harvest and consumption of green summer growing plants. However, in no-till stubble retained systems there are also potential disadvantages of grazing stubble (Fisher *et al.* 2010; 2011; 2012) including damage to soil structure and reduced water infiltration rates through localised compaction.

The value of grazing stubbles
Thomas *et al.* (2010) used agricultural models to calculate the value of grazing stubble to the profitability of a mixed farming enterprise. Grazing of stubble increased whole farm profitability in 70-90% of seasons and ranged from -$25 to +$110 at Cunderdin, WA and from -$40 to +$101 at Geraldton, WA. The value of the stubble was not equivalent to the value of its metabolisable energy (ME) or equivalent amount of energy from a supplementary

[17] © Grains Research and Development Corporation, Canberra, ACT (2010), 12 November 2013.

feeding source. The value of grazing crop stubbles to farm profitability was overestimated by the ME value of the intake, therefore the value of grazing crops cannot be predicted using energy intake from stubble. This was due to alternative feed sources being available at that time of year in most seasons, including dry annual pasture and perennial pasture, which were underutilised when stubbles were grazed.

Effect of grazing stubble on subsequent crops

Livestock can form a valuable part of conservation farming systems and contribute to production and risk management (through diversity). There is relatively little (<10%) or no effect on subsequent crop growth and yield if excessive grazing is avoided and a minimum groundcover of 70% or 2 t/ha of cereal stubble is retained (Bell *et al.* 2011; Hunt *et al.* 2011). In this study the grazed and ungrazed plots had similar moisture levels at 0-40 cm on 16 March, but the ungrazed area stored more water at depth, probably due to better infiltration rates rather than reduced evaporation. Lower infiltration in the grazed plots was apparently due to damage by raindrop impact rather than direct physical effects on soil as a result of grazing. Physical soil effects of stock trampling were shallow and transient, and reductions in subsequent crop yield were rare. The small yield penalty should be weighed against the benefits of grazing the stubble.

Grazing livestock can potentially increase soil strength and bulk density and reduce macro-porosity and infiltration (Hunt *et al.* 2012a). Although surface hydraulic conductivity can be reduced by between 20 and 60% infiltration is reduced to a much lower degree, especially in southern Australia where rainfall events are less intense (Bell *et al.* 2011). Also the effects of reduced hydraulic conductivity induced by grazing cannot be accurately quantified as they are confounded by the reduced groundcover. Furthermore, livestock have not been found to increase soil penetration resistance above 2 MPa which is the minimum requirement to significantly limit plant root growth (Bell *et al.* 2011). Any damage is generally shallow and short-lived as it is ameliorated by tillage, the soil's natural wetting-drying cycles and biological activity. Factors such as crop rotation and weed control are more important to crop growth and yield than the minimal effects of light to moderate grazing which is unlikely to have a detrimental impact (Jones and Ferrier 2012).

In southern NSW, soil nitrogen levels have also been shown to be higher, and wheat yield and protein were the same or higher, following grazing by sheep, which was attributed to more rapid nitrogen cycling (Table 14).

Table 14. Plant available water (PAW), mineral nitrogen at sowing, grain yield and grain protein following different grazing management of stubbles in the phase 1 experiment at Temora, New South Wales (from Hunt *et al.* 2012a), reprinted with permission[18].

	PAW at sowing (mm)	Mineral N at sowing (kg/ha)	Grain yield (t/ha)	Grain protein (%)
		2010 (canola)		
Nil graze	155	178	4.1	-
Stubble graze	110	205	4.2	-
Winter graze + stubble graze	99	279	4.0	-
LSD (P = 0.05)	19	53	ns	-
		2011 (wheat)		
Nil graze	201	93	4.6	13.0
Stubble graze	183	126	4.6	13.5
Winter graze + stubble graze	187	199	5.2	13.0
LSD (P = 0.05)	11	49	0.2	0.6
		2012 (wheat)		
Nil graze	203	99	4.7	10.5
Stubble graze	192	144	4.8	10.9
Winter graze + stubble graze	196	168	4.7	11.2
LSD (P = 0.05)	ns	38	ns	0.5

Key details and results of experiments on grazing of stubbles in south-eastern Australia are presented in Appendix 2.

3.5 Disease carry over in retained-stubble systems

The adoption of no till and retained-stubble systems has been possible with the availability of chemicals to control pests and weeds. Conventional cropping systems relied on cultivation and burning of stubble to exert some control over these production-limiting problems, particularly weeds (Scott *et al.* 2010). In Australia many diseases have been controlled through breeding for tolerance of resistance to diseases, particularly in cereals, with fungicides ideally used only as a backup tactic for new diseases, or if there is a breakdown of existing resistance mechanisms.

Longer term carry over of stubble

Stubble may carry over beyond one year. This can add to the amount of stubble to be sown through, but carry-over stubble can also be a source of disease, not only in the immediate following crop but also the subsequent crop.

Radford *et al*. (1992) working at Billa Billa, Queensland, reported that two kinds of stubble were present at harvest in the zero-tilled, retained-stubble treatment. At harvest during 1986 there was 2.0 t/ha of fresh stubble and 0.8 t/ha of stubble from the previous harvest. Similarly, at harvest during 1987 there was 2.1 t/ha of fresh stubble and 0.4 t/ha of older stubble.

Bhathal and Loughman (2001) monitored 17 paddocks in WA in a lupin-wheat rotation. Between 44 and 92% of the stubble present at wheat harvest was present in the following lupin crop (Figure 17). However, just 1-8% of the original stubble remained when the next wheat crop was sown 18 months later. The 18-month-old stubble was tested for the presence

[18] ©FarmLink Research Ltd (2012), 15 October, 2013.

of infectious spores and was found to cause disease (*Septoria nodorum* blotch and yellow leaf spot) in six out of 44 cases in wheat.

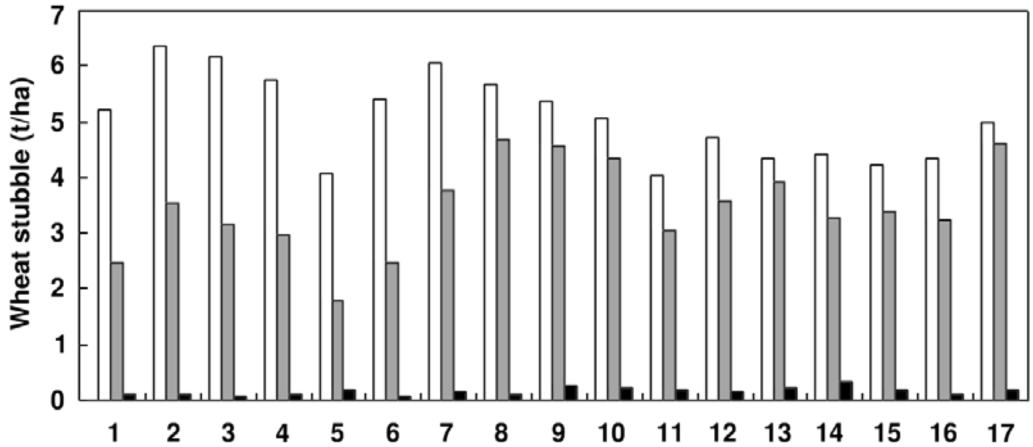

Figure 17. Weight of wheat stubble at harvest (open bar), in the following June in a lupin crop (six months; shaded bar) and in the next June in a wheat crop (18 months; solid bar) in 17 paddocks in a lupin-wheat rotation in WA (from Bhathal and Loughman 2001), reprinted with permission[19].

In southern NSW eyespot and take-all were also associated with retained stubble (Murray *et al.* 1991). In a no-till system with a wheat-lupin rotation, eyespot incidence on tillers of wheat was 36% with retained stubble, compared with 7% for the stubble-burnt system in the wet season of 1983. During 1983 and 1984 eyespot incidence on tillers was related to loss in grain yield. It was proposed that the very dry season of 1982 had prevented the breakdown of the wheat stubble in the lupin crop and so the wheat crop sown 1983 was infected by disease surviving on stubble carried over from 1981.

3.6 Diseases in retained-stubble systems

The practice of retaining, compared with burning stubbles, may significantly increase disease, particularly those diseases that survive in stubble. Increases in wheat disease with stubble retention have been noted for crown rot (*Fusarium pseudograminearum, F. culmorum*), common root rot (*Cochliobolus sativus (*syn. *Bipolaris sorokiniana*)), yellow leaf spot (*Pyrenophora tritici-repentis*), eyespot (*Oculimacula yallundae* (syn *Tapesia yallundae*, *Pseudocercosporella herpotrichoides*)) and take-all (*Gaeumannomyces gramininis* var *tritici)*(Scott *et al*. 2010). Recent evidence has emphasised the increased risk from yellow leaf spot, crown rot and rhizoctonia (Murray and Brennan 2009), while Septoria leaf blotch (*Septoria tritici*) may re-emerge as a significant disease.

Yellow leaf spot
Yellow leaf spot is an important disease of wheat throughout the Australian cropping area. It was the most important disease of wheat in WA by both potential and actual loss, and ranked as the most important disease based on present losses in the northern region of GRDC and third on potential losses (Murray and Brennan 2009). The disease was thought to be less important in the GRDC southern region (Table 15). Murray and Brennan (2009) conducted their survey of plant pathologists during the dry seasons before 2009; since the run of dry years ended during 2010 the importance of yellow leaf spot may need to be re-assessed.

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[19]© CSIRO Publishing (2001), 24 October, 2013.

While yellow leaf spot remains a commonly occurring disease in the southern areas there is debate about its importance and the value of fungicide control measures (Clarry 2013).

Table 15. The ranking of potential yield losses (with no management) and the present yield losses (with current management) by GRDC region for major diseases of wheat (from Murray and Brennan 2009), reprinted with permission[20].

Disease	Northern		Southern		Western		Australia	
	Potential	Present	Potential	Present	Potential	Present	Potential	Present
Yellow leaf spot	3	1	6	7	1	1	2	1
Stripe rust	1	2	2	1	5	5	1	2
Septoria nodorum	24	24	25	18	2	2	7	3
Crown rot	4	4	3	4	10	8	5	4
Root lesion nematode *P. neglectus*	9	6	4	5	3	3	6	5
Rhizoctonia barepatch	26	26	10	3	4	4	10	6
Cereal cyst nematode	26	26	1	2	12	17	3	7
Root lesion nematode *P. thornei*	5	3	13	10	15	14	9	8
Common bunt	11	14	5	12	9	12	11	16
Stem rust	2	9	7	21	7	10	4	17

Yellow leaf spot is a stubble-borne disease. The fungus survives as mycelia in stubbles of infected crops. Under wet conditions, small black fruiting bodies (*pseudothecia*) swell and eject spores (*ascospores*) which fly less than 10 cm from the stubble (Simpfendorfer 2013) and establish leaf lesions in seedlings. These ascospores are the primary inoculum for initiating infection in a new crop.

Lesions initiate as small, dark brown to black spots, which expand forming lesions with a necrotic (dead) tan centre surrounded by a ring of yellow chlorotic tissue (Platz 2011). Lesions coalesce killing leaves. Under wet conditions asexual spores (*conidia*) are produced on dead and dying tissue and these are responsible for subsequent infection. The conidia can be spread (up to 100 m) with wind. However, as the conidia are being produced on old lesions in the lower canopy, most are trapped within the canopy of the current wheat crop and predominantly result in the spread of symptoms from the lower to the upper canopy (Simpfendorfer 2013).

Wheat stubble can remain infective for several years (Wright and Sutton 1990; Anon 2011f) and in dry seasons the carryover of old stubble into a second new crop may result in infection. Small amounts of infected stubble can contribute to yellow leaf spot infection. Rees *et al*. (1982) demonstrated that one-year-old infected stubble applied at rates as low as 168 kg/ha caused a 28% yield reduction (Figure 18).

[20] © Grains Research and Development Corporation (2009), 12 November, 2013.

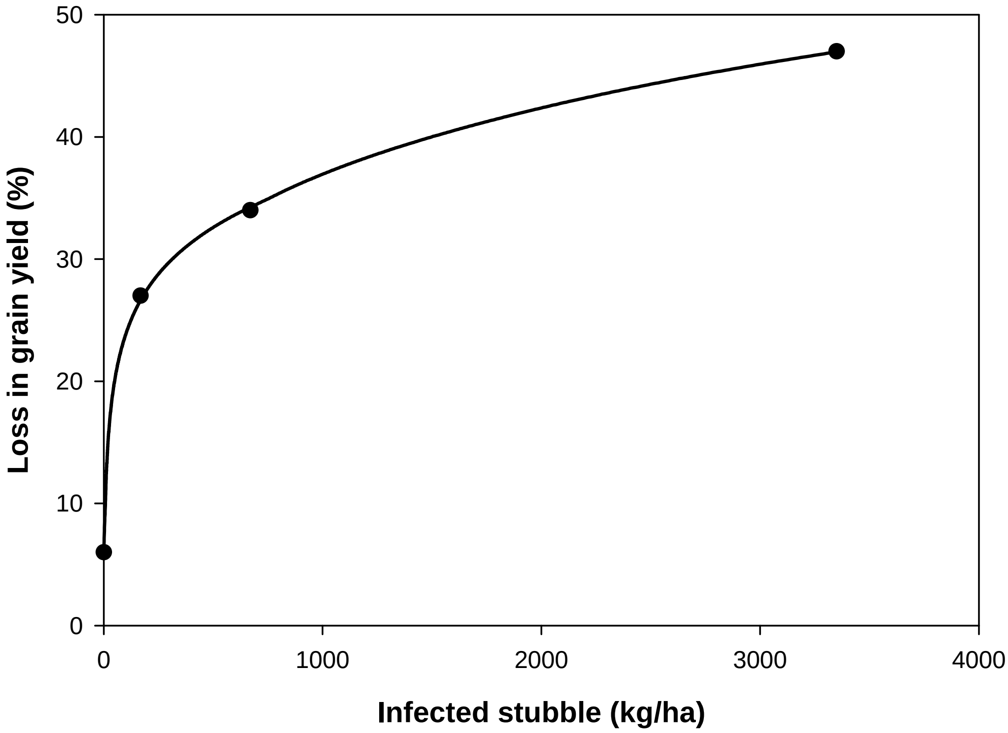

Figure 18. Relationship between % yield loss, relative to a sprayed treatment, and the amount of infected stubble applied to the soils surface. Amounts of infected stubble applied were nil, 168 kg/ha, 670 kg/ha and 3350 kg/ha. (from Rees *et al.* 1982), reprinted with permission[21]

Yellow leaf spot was the wheat disease most frequently misdiagnosed in the northern NSW during 2012 (Simpfendorfer 2013), with symptoms being confused with nitrogen deficiency related to transient waterlogging, herbicide phytotoxicity and frosts during flowering. Similar concerns were raised in southern NSW (Clarry 2013). Aluminium toxicity has also been reportedly misdiagnosed as yellow leaf spot (Anon 2012c). These misdiagnoses can lead to unnecessary spraying with fungicide.

The following checklist has been devised to help growers accurately identify yellow leaf spot (from Pritchard 2013; Simpfendorfer 2013):

- Wheat stubble is present.
- Black fruiting bodies are visible on the stubble.
- Visible symptoms include small brown spots with yellow margins that become more elongated with age indicate the presence of yellow leaf spot.
- The pattern of lesions is consistent with yellow leaf spot. On an individual infected tiller there should be a clear pattern of distribution on the leaves with frequency and size greatest on the older, lower leaves (they have been infected earlier and had time for fungal growth to spread), and fewer and smaller lesions occur on younger leaves.

Murray and Brennan (2009) have suggested that investment in breeding programs contributed 43% toward the control of yellow leaf spot, with cultural means and fungicide control accounting for 33% and 23%, respectively. The major cultural controls are removal or

[21] © CSIRO Publishing (1982), 24 October, 2013.

burning of stubble and improved crop sequencing using non-host crops such as barley, canola, chickpea, lupins or field peas (Platz 2011). Green barley plants do not show symptoms of yellow leaf spot, but barley stubbles can host the pathogen and generate inoculum in the following season.

Control of yellow leaf spot requires management of inoculum levels (Anon 2011f, 2011b; Platz 2011; Anon 2012c; Clarry 2013; Pritchard 2013; Simpfendorfer 2013), which may be lowered by:

- Rotating susceptible crops with non-host crops.
- Using resistant wheat cultivars (see Anon 2011f for southern region).
- Reducing or eliminating surface stubble by incorporation, grazing or burning.
- Applying foliar fungicides.

The first three decisions need to be made prior to sowing (Simpfendorfer 2013), while the last is an in-crop decision.

The use of seed or fertiliser fungicides is viewed as ineffective against yellow leaf spot (Anon 2012c; Pritchard 2013; Simpfendorfer 2013). The fungus survives on the dead tissue in the centre of the lesion. All fungicides, once inside the leaf, move in the xylem. Cells killed by the toxin released by the yellow leaf spot fungus include the xylem. Therefore there is no xylem activity in yellow leaf spot lesions (dead leaf tissue) and a fungicide will not penetrate this region (Simpfendorfer 2013). In addition xylem only flows from the base of the leaf towards the tip. As the fungicides do not move toward the leaf base, only leaves that have emerged at the time of a fungicide application are protected for up to three weeks. Inoculum continues to be produced by both the stubble and the dead parts of lesions and newly emerging leaves and leaf area not contacted by the fungicide (for example, unemerged base of each leaf) are unprotected (Simpfendorfer 2013).

It is unlikely to be economic to apply fungicides to control yellow leaf spot during winter in the GRDC southern region. However, where wet conditions persist into spring fungicides can provide some control (Anon 2011f). Maximum benefits are obtained by keeping the flag (F), F-1 and F-2 leaves free from disease during grain fill (Platz 2011). This guideline dictates spraying between flag leaf emergence and late booting (Anon 2012c) or about 90% flag leaf emergence (Platz 2011).

Varieties are known to vary in their susceptibility to yellow spot in the field (Rees and Platz 1979). Subsequent breeding in WA has produced cultivars with a moderate but useful level of resistance (Wilson 1995; Wilson and Loughman 1998) and this research effort is continuing (Shankar 2010).

Crown rot

While crown rot is an important disease of wheat throughout the Australian cropping area, it is more significant in the GRDC northern and southern regions than in the Western Region (Murray and Brennan 2009) (Table 15). Crown rot in southern NSW is caused by both *Fusarium pseudograminearum* and *F. culmorum,* with *F. culmorum* thought to be more common in higher rainfall and irrigated environments (Milgate 2013). Both are fungal pathogens of grasses, and attack all cereals. However, a survey of the incidence of crown rot across 76 paddocks in southern NSW during 2012 showed crown rot was extensive (Minehan 2013). Producers and advisors had incorrectly attributed ‘white heads’ to frost, take-all, drought stress or nutritional deficiencies (Minehan 2013).

Murray and Brennan (2009) suggested that cultural means and breeding account for 60% and 40% control of crown rot, respectively, with no opportunity for control by pesticides. The major cultural control options available to growers include improved crop sequencing, burning of stubble, and the recent innovation of inter-row sowing. Non-cereal crops such as canola, chick peas and lupins can act as break crops and may be more profitable than wheat in paddocks with medium to high levels of inoculum (Milgate 2013).

Burning stubble rather than retaining stubble provides partial control of crown rot. The more recent research of Simpfendorfer *et al*. (2006b) supports the earlier work of Burgess *et al*. (1993; 1996). Although incidence of crown rot was lower in burnt stubble treatments compared with retained-stubble systems (Figure 19), burning only provided partial control. While burning destroys the stubble above ground the crown rot fungus survives in the crowns below ground (Simpfendorfer *et al.* 2006b).

The capacity of crown rot to achieve high levels of infection from low initial infection levels minimises the benefits of partial control. The reduction in inoculum level achieved from burning often only results in a marginal benefit in a subsequent wheat crop (for example, Figure 19a in 1988-1990) (Burgess *et al.* 1993).

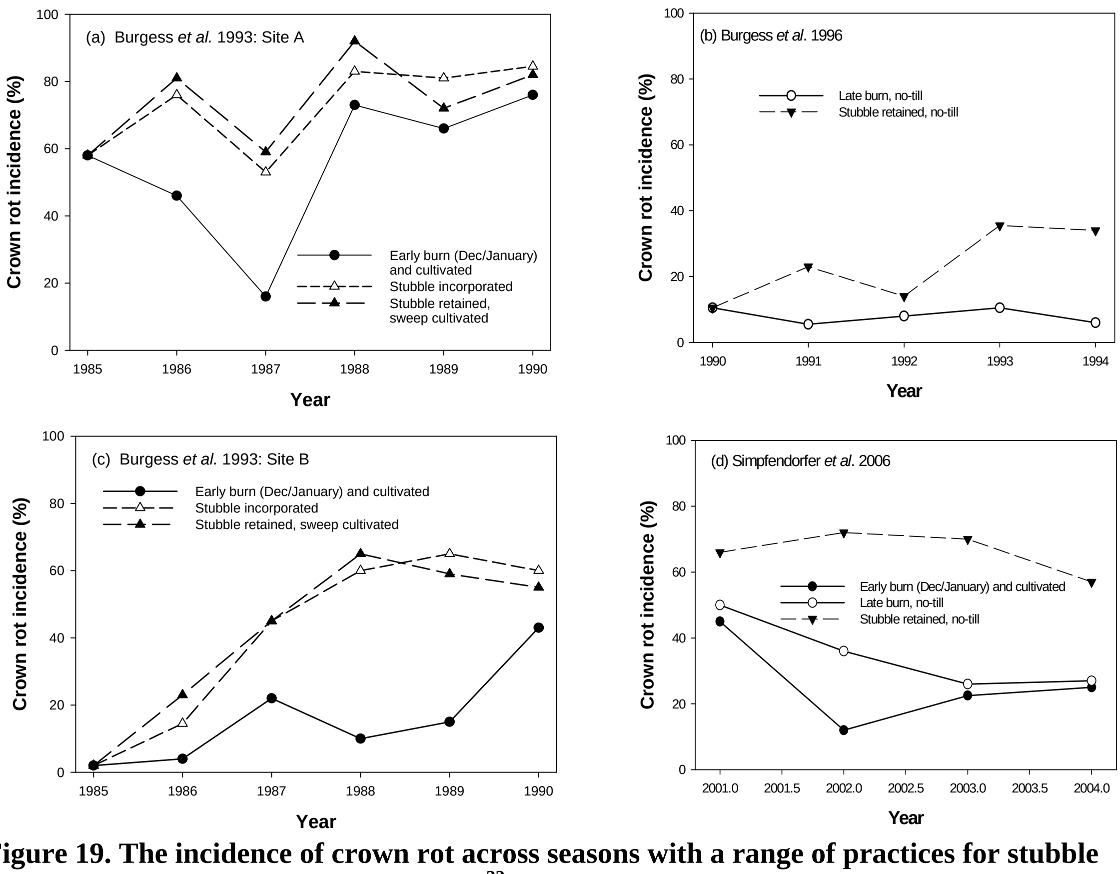

Figure 19. The incidence of crown rot across seasons with a range of practices for stubble management, reprinted with permission[22].

Research by Simpfendorfer *et al*. (2004; 2007) suggests physical separation of new wheat seedlings from the old crowns of the previous wheat crop can inhibit the infection by the

[22] ©CSIRO Publishing (1993), 24 October, 2013.
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crown rot fungus *Fusarium pseudograminearum,* and the common root rot fungus *Bipolaris sorokiniana*. The authors suggested that inter-row sowing and use of wider row spacings (≥ 300 mm) could reduce the rate of inoculum build up in a paddock. They proposed that inter-row sowing could be a valuable component of an integrated disease management system. In the presence of crown rot, yield advantages accrued when sowing wheat in the inter-row (Table 12a). A similar advantage was noted in the presence of take-all, another stubble borne disease, but also where no stubble borne disease was detected (Table 12b).

While the current bread wheat varieties Sunco and EGA-Wylie⊕ have some resistance to crown rot, crown rot resistance is only one aspect of cultivar selection and it has been observed that grain yield in the presence of crown rot does not align with known resistance (Long and Penberthy 2013; Milgate 2013). Some susceptible cultivars may out-yield cultivars with known resistance. The aim is to breed cultivars with a combination of high yield capacity and crown rot resistance.

The resistance in Sunco has been located on chromosomes 1D, 3B, 4B and 7A, with the most important quantitative trait loci (QTL) for resistance on chromosome 3B (Poole *et al.* 2011a). Li *et al.* (2012) validated the previously identified wheat QTL on 3B using the cultivar 'Ernie' as a resistant parent and developed more closely linked markers. They believed that their results warranted the incorporation of the locus into breeding programs.

Rhizoctonia

Rhizoctonia (*Rhizoctonia solani*) is a fungal disease that occurs throughout southern Australia, particularly on sandy soils in lower rainfall regions, and extends to higher rainfall regions such as the slopes of NSW (McKay *et al.* 2012). In the GRDC southern region, Murray and Brennan (2009) concluded that rhizoctonia occurs in 76% of years, affecting more than 50% of the cropped area. Australia-wide annual production losses due to rhizoctonia have been estimated at between $59 and $77 million (Roget 2006; Murray and Brennan 2009).

Rhizoctonia infections have become more severe and widespread with the increased adoption of minimum tillage practices, intensification of cereal cropping, and higher frequency of drought years (Roget 1995; Anon 2008a; Gupta 2010; Wherrett undated).

Rhizoctonia inoculum levels can vary significantly within and between seasons. This fungus is adapted to dry conditions; levels will increase during drought and dry summers and decline following summer rainfall events of more than 25-50 mm during one week (Gupta 2010; Gupta *et al.* 2012; McKay *et al.* 2013). McKay *et al.* (2012) reported high inoculum levels in southern Australia in drought conditions during 2008-2009 and low inoculum levels during 2010 following a favourable growing season and wet summer.

Tillage has been shown to effectively reduce rhizoctonia inoculum levels as it breaks up the fungal hyphal networks (Wherrett undated). A non-host crop such as canola, mustard, field peas, chickpea, a medic pasture or long fallow have been shown to minimise inoculum levels and increase yield of the following wheat crop by up to 47% (McKay *et al.* 2012; McKay *et al.* 2013).

Disease-suppressive soil activity, a function of microbial population, composition and activity, has reportedly provided complete control of rhizoctonia at Avon (SA), 5-10 years after the adoption of full stubble retention, limited grazing and high nutrient inputs (Roget

2006; Anon 2008a). However, the SA experience must be kept in geographical context as there is no evidence of suppressive soil activity in other areas of the GRDC southern region (A Milgate, pers. comm.).

Research results from SA have also shown the potential suppressive ability of soils can be enhanced by increasing inputs of biologically available carbon (C) and the C:N ratio through stubble retention, intensive cropping systems, minimal grazing and minimum or zero-tillage (Anon 2008a; Gupta and Reddy 2010; McKay *et al.* 2012). This is in contrast to reports of increased incidence and severity of rhizoctonia under reduced tillage systems where suppression is not present.

Roget (2006) and Gupta (2010) found that removal of carbon inputs by burning and grazing can reduce the soil C:N ratio, microbial activity and suppressive potential. Nitrogen levels of 40-60 kg/ha (at 0-10 cm) can switch off suppressive activity. However, in low rainfall, low N input systems, suppression is more robust and once achieved is not affected by high mineral N levels (118 kg/ha) (Cook *et al.* 2010).

Rhizoctonia levels may increase during the first few years of a stubble retention system as the rhizoctonia pathogen utilises crop residue as a feed source and fungal hyphae will remain intact in the absence of tillage, but can then decline if suppression is present (Roget 1995). Rhizoctonia inoculum levels may also decline where stubble retention results in elevated levels of conserved moisture.

Cultivation below the seed in combination with a seed fungicide is recommended in paddocks considered a high risk for rhizoctonia (Huberli *et al.* 2012). A number of fungicide seed treatments are registered for suppression of rhizoctonia in wheat and barley (92 g/L difenoconazole; 23 g/L metalaxyl-M - Dividend®; 240g/L penflufen - EverGol® Prime and difenoconazole 66.2 g/L; metalaxyl-M 16.5 g/L; sedaxane 13.8 g/L - Vibrance®). Trials in SA found these products to increase yield by an average of 5% (McKay *et al.* 2013) while a separate experiment found penflufen to reduce the incidence of root infection by approximately 60-70% (Cross and Druce 2012). Trials using Dividend® and Vibrance® showed a 6.4% yield increase and reduction in disease rating from 2.13 to 1.77 (on a scale of 1-3) in barley (Klein *et al.* 2012). Up to 15% yield increase has been shown with a split application of fungicide on the soil surface and below the seed at sowing using a knife point sowing system.

Rhizoctonia can be minimised by avoiding plant stress and promoting early vigour through timely sowing, ensuring adequate nutrition and avoiding sulfonylurea herbicides (Gupta 2010). Control of the 'green bridge' during the inter-crop period will also avoid inoculum build-up before sowing and conserve moisture. PreDicta B® tests can identify high risk paddocks, although regional differences can occur. For example, low levels of inoculum may be recorded following summer rainfall in southern NSW but significant crop damage can occur if this is followed by cold winters (McKay *et al.* 2012).

Septoria tritici blotch

Septoria tritici blotch, also called Septoria leaf spot or speckled leaf blotch of wheat is caused by the fungus *Mycosphaerella graminicola* (anamorph *Septoria tritici*). While potentially an important disease of wheat the widespread adoption of partially resistant wheat varieties since the early 1980s has seen Septoria tritici blotch become a minor disease in Victoria (Anon 2012b) and the GRDC southern region.

Septoria tritici blotch survives over summer on stubble. Following rains or heavy dew during late autumn and early winter, fruiting bodies (*perithecia*) release wind borne spores (*ascospores*) from the previously infected stubble. These spores can be spread across large distances (Anon 2012b). These early ascospore infections cause blotches on the leaves of wheat. Within these blotches a second type of fruiting body, pycnidia, are produced and disperse by water splash to other leaves. Septoria will be most severe in seasons of above-average spring rainfall.

Practices such as rotation of diverse crops and application of fungicides, have been employed to control this disease and subsequently reduce yield losses. However, the durable partial resistance in current commercial varieties has controlled the disease. Research into improved resistance continues (Raman and Milgate 2012). If susceptible and highly susceptible varieties are grown, this disease is likely to cause annual average losses of up to 20%, with individual crop losses much higher (Anon 2012b).

A high number of ascospores are released early in the season so it is best practice to avoid sowing wheat into infected stubble and avoid early sowing. Destroying stubble by grazing or cultivation will reduce the number of spores available to infect the new season's crop. However, this approach will only be effective if undertaken on a district basis, because of the distance the ascospores can be carried in the wind.

3.7 Pests and stubble retention

Evolving farm management practices and varying climatic patterns are contributing to a shifting complex of invertebrate and vertebrate pests. A shift towards minimum tillage systems has increased invertebrate numbers and biodiversity. The associated increase in pesticide use has influenced pest complexes and accelerated selection pressure for resistance. These farming systems create more favourable conditions for many pests, such as slugs, and also influence beneficial species such as carabid beetles which are predators of slugs and wireworms (Hoffmann *et al.* 2008).

In conducting this review the limited documentation of pest-related issues from the GRDC northern region (Freebairn 1986; Wilson-Rummenie *et al.* 1999) and the western regions (Micic *et al.* 2007; 2013) was noted. Wilson-Rummenie *et al.* (1999) identified no invertebrate pest issues associated with conservation farming in Queensland, while Freebairn (1986) noted that "..insect pests have not increased greatly with the adoption of stubble mulching...wireworm and false wireworm numbers can sometimes increase with summer crops". Micic *et al.* (2007) and Micic *et al.* (2013) described issues similar to those reported in this review for high rainfall or southern areas of WA. The GRDC southern region provides abundant evidence of pest-related issues associated, at least in part, with stubble retention.

Snails and slugs
The shift from burning to retaining stubble, accompanied by reduced tillage, has resulted in an increase in snail populations and elevated their pest status (Baker 1998). Snails that are agricultural problems in south-eastern Australia include the common white snail (*Cernuella virgata*), white Italian snail (*Theba pisana*) and the conical snail (*Cochlicella acuta*) and their life cycles have been described by (Baker 2008) in a 20 year study. Snails can damage emerging crops, clog machinery at harvest and contaminate grain (Leonard 2003). Control measures over summer-autumn include burning stubbles, cabling or bashing, and using

rollers to crush snails (Leonard 2003; Hayes 2013). Baiting is effective on larger snails in-crop.

More recent reports indicate the severity of slugs has increased with adoption of stubble retention: stubble provides a suitable habitat for survival and build-up of slug populations (Horne and Page 2006). The main problem species of slug are the black keeled (*Milax gagates*) and grey field slug (*Deroceras reticulatum*), with the brown field slug (*D. panormitanum*) becoming more important (Nash 2012). Increased area and frequency of retained stubble has reduced snail and slug management options. Burning and cultivation are effective methods to control slugs and snails and are valuable management strategies when high populations of slugs or snail are expected (Nash 2012).

High stubble loads and conditions that favour snail survival are in part responsible for the highest snail numbers ever reported in South Australia during 2009. A year-round integrated management approach is recommended, which includes a high temperature burn. A colder burn may only reduce numbers by up to 50% (Perry 2012).
Trials have shown that the best option for control of slugs is baiting combined with cultural practices including cultivation and burning. Victorian grain growers previously implementing no-till systems have reportedly returned to cultivation to control slugs (Lush 2013).

Weevils
Weevils feeding on vegetative parts of crops can cause significant damage. Population build-up is favoured by minimum tillage and retained stubble. Removal of stubble through cultivation and burning destroys habitat and reduces numbers. Behavioural habits of crop weevils mean they are difficult to control with pesticides (Umina 2013).

False wireworms
False wireworms (*Gonocephalum macleayi*, *Pterohelaeus alternatus*, *P. darlingensis*) feed on crop residue and damage usually occurs in crops following stubble incorporation or where stubble is retained on the soil surface. Economic injury levels for false wireworms depend on the amount of stubble retained and also whether it is buried or retained on the soil surface.

The widespread adoption of stubble retention may have contributed to an increase in false wireworm numbers reported in southern Queensland. Removal of stubble could provide a management option to control populations (Robertson 1993).

Bronzed field beetle
The larvae of bronzed field beetle (*Adelium brevicorne*) are problematic pests of germinating canola and lupins. Stubble retention systems that leave crop residue on the surface provide shelter for these crop pests (Perry 2012). Removal of plant residue before egg laying during late February to early March can reduce or eliminate bronzed field beetle populations.

Earwigs
The European earwig (*Forficula auricularia*) is a pest of seedling crops including canola, cereals and legumes. Crop residue retained on the surface creates a favourable environment for survival and breeding. Removing plant residues before sowing is the most effective strategy to control earwigs (Perry 2012).

Millipedes
Portuguese millipede (*Ommatoiulus moreletii*) populations have increased in South Australia in minimum tillage cropping systems during recent years. This is likely to be a result of increased soil moisture and organic matter levels. Millipedes cause the most damage to emerging canola seedlings. Strategies that remove crop residues are the most effective control options (Perry 2012).

Slaters
Slaters are generally considered to be a minor pest of broadacre crops, but have caused increasingly significant damage to broadacre crops during the last five years (Anon 2013c). The most common species in Australia is the native 'flood bug' (*Australiodillo bifrons*) (Anon 2008b). However, high populations of slaters do not necessarily mean significant crop damage will occur, as slaters feed predominantly on decaying plant matter and rarely on crop seedlings (Anon 2013c).

There is a strong correlation between populations of slaters and stubble retention and minimum tillage. Slaters will not survive exposed, dry conditions and retained stubble provides a cool, moist habitat which enables survival and development (Anon 2008b, 2013c). There are no pesticides currently registered to control slaters in broadacre crops and foliar sprays have poor efficacy (Anon 2013d). Populations can be controlled by cultivation (Anon 2008b).

Beneficial species
Stubble retention and the associated increase in soil organic matter should support an increase in beneficial predator species such as some beetles and spiders. In the absence of stubble burning, these predators could reach and maintain populations sufficient to suppress pest infestations, particularly where direct drilling is used. However, previous studies have found little effect of retaining stubble on predator populations (Schaber and Entz 1994), or have been inconclusive. Stubble retention does however create a favourable microclimate for invertebrate species enabling them to survive hot, dry summers.

The beneficial carabid beetles (Coleoptera: carabidae) are important for biocontrol of pests in agricultural crops throughout the world. They have been found in Australian broadacre cropping systems where they are potential biocontrol agents for several species of exotic pests. Studies have shown that populations of carabids increase when tillage is reduced (Horne 2007). However, the beneficial effects of carabids as predators are generally not seen due to the use of broad-spectrum insecticides which are lethal to flightless carabid species (Horne 2007).

Mice
Mouse plagues have increased in frequency as a result of stubble retention, a range of diverse crops, reduced cultivation and reduced grazing pressure from livestock. The changed farming systems provide habitat and a food supply that is more abundant and higher in quality than conventional systems, due to reduced grazing of stubble, more diverse crop species and an absence of cultivation. The availability and quality of the feed source is the primary determinant of mouse populations (Mutze 2011). These changed circumstances have led to both an increase in mouse numbers and greater damage for the same number of mice.

Whereas mouse plagues occurred every 6-7 years (before 1970), they are now likely to occur once every four years.(Mutze 2011). Changes in cropping systems have not only improved the feed supply and quality, but also provide a longer time period during which high quality food and shelter is available. Mouse plagues are now reported in consecutive years, which historically rarely occurred (Mutze 2012).

The 2010 mouse plague on the Eyre Peninsula, SA, caused an estimated yield loss of $20-40 million. Risk factors identified following this plague included more stubble paddocks and fewer pasture paddocks, ungrazed versus grazed stubbles or pastures, tall standing stubbles versus burnt, rolled or slashed stubbles, and stubbles incorporated at sowing rather than earlier (Mutze 2011).

3.8 Stubble retention and herbicide application

Herbicide efficacy is an issue with application of herbicides in retained-stubble systems. The stubble can interfere in the application of herbicides by being a barrier to the application of soil-applied, pre-sowing herbicides and foliar applied herbicides both in-fallow and in-crop. Foliar or soil-applied herbicides may intercept the standing stubble, which would interfere with the spray's ability to contact weeds or the soil surface. A portion of the herbicide may lodge in the stubble and then leach from the stubble with rainfall, or volatilise (Banks and Robinson 1982; Petersen and Shea 1985; Dao 1991; Wolf *et al.* 2000).

Banks and Robinson (1982) applied metribuzin with a high volume boomspray application (280 L/ha of water) and found that only 30% of the herbicide reached the soil surface under 2.25 t/ha of wheat straw, less than 15% reached the surface under with 4.5 t/ha of straw, and less than 5% with 9 t/ha of straw. Subsequent watering (with 50 mm of simulated rainfall) leached some herbicide from the stubble to the soil and increased these estimates to 45%, 39% and 35%, respectively.

Shaner (2013) found that herbicides vary in their level of binding to crop residue. Of the three herbicides tested, metalochlor (for example, Dual® Gold) had the highest level of herbicide binding to wheat residue (74.3%), followed by atrazine (49.9%) and pyroxasulfone (Sakura®; 37.8%). There was a linear relationship between the percentage of residue groundcover and herbicide interception (Shaner 2013)(Figure 20), Shaner also reported that most herbicide washed off stubble residue (sorghum) with 5 mm of rainfall. More herbicide was washed off with increasing rainfall and subsequent rainfall events, and the amount leached also varied with the type of herbicide applied (Shaner 2013). Some herbicides can dissipate due to volatilisation (for example, metalochlor), photodegradation or microbial activity if sufficient rainfall is not received soon after application (Shaner 2013).

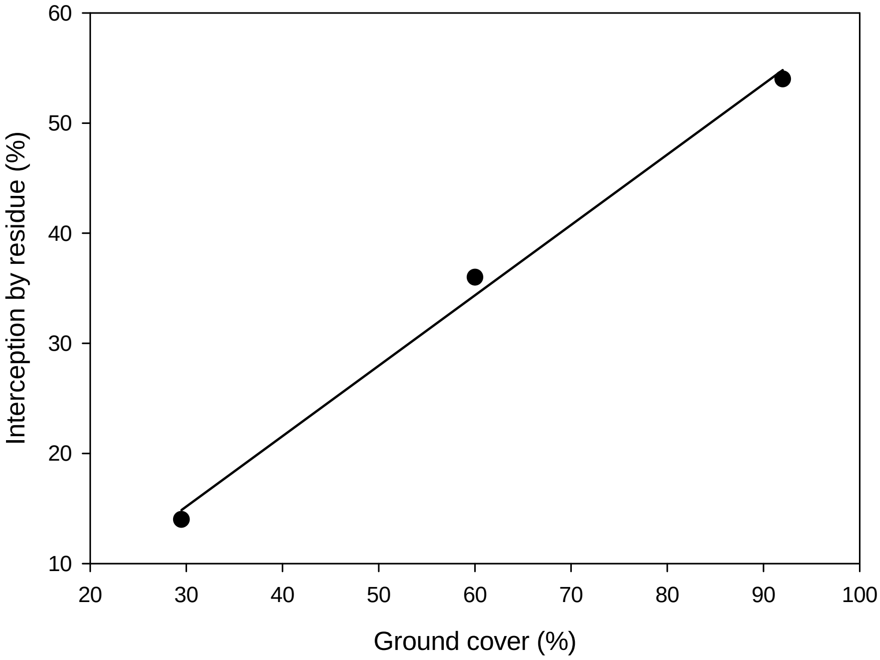

Figure 20. Relationship between groundcover (%) and herbicide interception by crop residue(%) (from Shaner 2013), reprinted with permission[23]

Summer weed control

Control of weeds during summer is commonly achieved using glyphosate, with some added herbicides for the control of some difficult weeds (for example, fleabane; Haskins 2011). The efficacy of glyphosate can be compromised by dust on the leaves of weeds, and moisture stress in the weeds can reduce general herbicide effectiveness (Newman *et al.* 2012). The presence of stubble in summer fallows provides an additional barrier between the spray nozzle and the weed to be contacted by the herbicide. However, as stubble is burned just before sowing, the difficulties of spraying weeds in stubble during summer are the same whether stubble is retained, or subsequently burnt in later autumn-early winter.

Pre-emergent herbicide application

When trifluralin was sprayed, coverage of the spray on water sensitive cards placed on the ground was affected by water rate used (Borger *et al.* 2012). At Cunderdin (3.3 t/ha of stubble) there was 25%, 17% and 9% spray coverage of the cards at 100, 75 and 50 L/ha of water and at Wongan Hills (1.5 t/ha stubble) there was 26%, 13% and 8% spray coverage (Borger *et al.* 2012). Higher coverage of the soil with the higher water volumes improved the effectiveness of trifluralin (Table 16).

In a series of experiments there was a trend for increased water volume used in spraying to increase the efficacy of herbicides applied pre-sowing (Table 16) with the greatest effect at Cunderdin during 2010 (Borger 2012) where the stubble load was high and a high water volume (150 L/ha) was used. Higher water volumes are generally recommended with retained stubble.

[23] ©Grains Research and Development Corporation (2013), 12 November, 2013.

Borger (2012) and Borger *et al.* (2012) suggest that solid droplets and coarse spray quality should be used with herbicides like trifluralin (low solubility) to penetrate stubble. However, Borger *et al.* (2013) found higher coverage on water sensitive cards from a medium droplet size compared with a coarse droplet. They concluded that, as control of ryegrass was unaffected by droplet size, a coarse droplet was still preferred to minimise spray drift.

Table 16. Control of annual ryegrass (% of no herbicide) by increased water volume at spraying in retained-stubble situations (Borger 2012; Borger *et al.* 2012; Borger *et al.* 2013).

Site	Herbicide	Water rate (L/ha)						
		30	50	70	90	110	130	150
Cunderdin, 2010	Triflur Xcel® at 2.5 L/ha	7	14	17	16	44	54	71
Merredin, 2010	Triflur Xcel® at 2.5 L/ha	79	86	90	86	93	90	97
Wickepin, 2010	Triflur Xcel at 2.5 L/ha and Sakura® at 118 g/ha	40	na[a]	45	na	na	na	53
Esperance, 2010	Triflur Xcel at 2.5 L/ha and Sakura® at 118 g/ha	88	na	90	na	na	na	91

Site	Herbicide	Water rate (L/ha)		
		50	75	100
Cunderdin, 2010	Triflur Xcel® at 2.5 L/ha	84	87	89
Wongan Hills, 2010	Triflur Xcel® at 2.5 L/ha	77	83	82

[a] not available

Some herbicides are more suitable for stubble retention systems than others. Common pre-emergent herbicides that will wash off the stubble after being intercepted and still provide effective weed control include Logran®, Glean®, atrazine, simazine, Terbyne®, Balance®, Boxer® Gold and Sakura® (Haskins 2012). Trifluralin, Stomp® and Avadex® Xtra can be tied up by the stubble so higher rates are needed (Haskins 2012).

However, more soluble herbicides (Boxer® Gold and Sakura®) gave similar improvements in annual ryegrass control with increased water volumes (Figure 21) (Borger 2010).

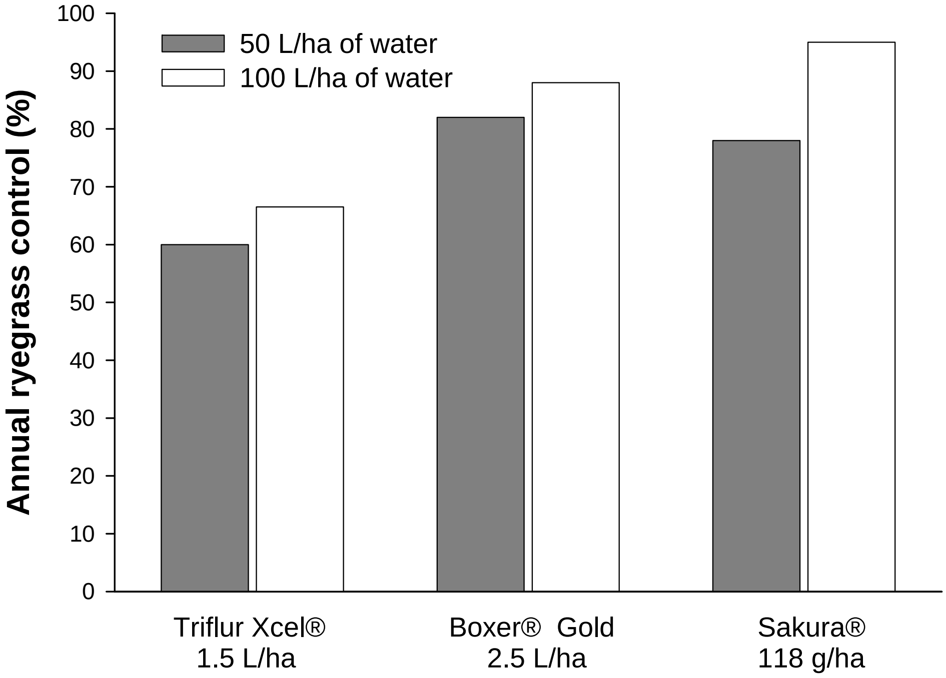

Figure 21. The control of annual ryegrass (% of no herbicide) by Triflur Xcel® at 1.5 L/ha, Boxer® Gold at 2.5 L/ha and Sakura® 850 WG at 118 g/ha, when herbicides were sprayed with 50 or 100 L/ha of water. Average stubble biomass at sowing was 4.6 t/ha (from Borger 2010), reprinted with permission[24].

It has also been suggested that in wide row spaced stubbles precision spraying could aid soil-applied herbicides in reaching the soil surface (Butler and Desbiolles 2008). Nozzles could be spaced at the same interval as the row spacing and the nozzles aligned with the middle of the inter-row space where least stubble would be expected (Condon 2013).

In the research of Borger *et al.* (2013) the stubble groundcover ranged from 50-90%, with the site mean coverage of the four sites ranging from 65-80%. However, the maximum ground cover advised by the manufactures of trifluralin (Anon 2009b), Boxer® Gold (Anon undated-a) and Sakura® (Anon 2011c) is 40-50%. It is clear that in the GRDC southern and western regions these herbicides are being used in stubbles with much higher groundcover than the manufacturers recommend.

Other management options for increasing herbicide efficacy in stubble retention systems include managing stubble at harvest. For example, spreading trash evenly and leaving stubble standing upright to maximise the amount of herbicide reaching the soil (Haskins 2012).

With higher ground speeds at sowing, soil from the sowing row is thrown to the inter-row space, reducing the effective rate of application of soil-applied herbicide near the seed and increasing effective application rates in the inter-row space. Higher ground speed with wide rows at sowing can be used to increase the application rates of pre-sowing soil-applied herbicides, as little herbicide remains near the germinating crop seeds (Haskins 2012). This combined with the interference that stubble causes to herbicide application has been solved

[24] ©Department of Agriculture and Food, WA (2010), 12 November 2013.

by using higher rates of application of some herbicides in no-till where incorporation is by sowing, than for incorporation by cultivation, (for example, label rates of trifluralin) (Anon 2009b).

In an inter-row sowing system resultant application rates are higher in the inter-row of the first crop and this is the site of sowing of a second crop, in the inter-row. Some combinations of crops, soils, herbicides and seasons may result in carryover of residual herbicide and limit the choice of species in the second crop (for example, Glean®or Lontrel® applied in a cereal crop may be a risk for a following canola crop).

Trials have shown that pre-emergent herbicides incorporated by sowing (IBS) have higher levels of crop safety compared with those applied post sowing pre-emergent (PSPE) (Haskins 2012). Additionally, tined seeders provide a higher level of crop safety compared with disc seeders, providing greater crop vigour for seven out of the 10 herbicides tested, greater weed control for eight herbicides and equal weed control for two herbicides (Haskins 2012).

Research in NSW demonstrated that tine seeders produced consistently better establishment and early crop vigour with all pre-emergent herbicides applied (IBS), irrespective of weed density, soil moisture and stubble load (Condon 2013). Knife point and press wheel sowing systems can accurately place seed at consistent depths and provide greater soil throw therefore enabling growers to use pre-emergent herbicides in minimum tillage systems with more confidence (Condon 2013). Existing disc seeders vary in soil throw (Haskins 2012) and industry is working on developments with disc seeding systems that enable more soil throw for reduced crop herbicide damage, seed boot shields with built-in soil deflectors and reversible or adjustable disc closers (Condon 2013).

Modified patterns of use of herbicides

In addition to the higher rates of application in retained-stubble systems (Haskins 2012) other patterns of herbicide use have emerged. As resistance to post emergent herbicides has developed in weeds a shift has been from in-crop herbicide application to pre-emergent herbicides. An additional change has been to modify usage patterns to use non-selective herbicides. Both strategies will inevitably lead to increases in herbicide resistance to these herbicides as is already occurring across southern Australia (Boutsalis *et al.* 2009).

***Crop topping*:** 'Crop topping' is where the mature or near mature crop is sprayed with a non-selective herbicide (glyphosate or paraquat) with the aim of preventing or reducing viable seed set of weeds without affecting the yield of the grain crop. Crop topping is used as part of an integrated weed management (IWM) to reduce the weed seedbank by controlling seed set of late germinating weeds and weeds resistant to in-crop herbicides. This technique has been used on pulse crops to control annual ryegrass with some success (Mayfield and Presser 1998; Lines *et al.* 2012). Further advantages accrue in desiccating pulse crops for a more even maturity and improved harvestability. However, pulse crops vary in suitability for this practice, and there are concerns with grain yield and quality losses. Field peas and narrow-leaf lupins are considered well suited to crop topping, with lentils less suited and chickpeas unsuited. Species suitability is summarised by Meldrum (2011). Crop suitability is related to earliness of maturity, with earlier maturity conferring suitability. As such there is a range of suitability within cultivars of a species (Lines *et al.* 2012) as well as between species. The link between crop maturity and suitability for crop topping could be the time of spraying, which has been determined by the maturity of annual ryegrass; spraying is recommended at the soft dough stage (Meldrum 2011) or the milky dough stage of the ryegrass (Lines *et al.*

2012) of the grass weed. Further, Meldrum (2011) advises against retaining seed from a crop which has been spray topped, as viability may be adversely affected. Peas for the sprouting market were also a concern due to potential damage to viability.

Crop topping has been used as a control option for wild radish (Walsh and Powles 2009) in a range of crops. Crop topping with glyphosate and Spray Seed® at crop maturity reduced seed production of wild radish by about 50%, while grain yield of wheat, lupin, barley and canola was unaffected at one site (Goomalling, WA, 1999). At a second site (Yorke, WA, 2001) seed production of wild radish was reduced by about 80% by crop topping at near crop maturity, and grain yield of wheat, barley and canola was unaffected; lupin yields were not reported. In both field experiments spraying earlier than crop maturity more effectively reduced seed production of the weed, but reduced crop yield. Bennet *et al.* (2009), at Cummins, SA also found reduced yield of wheat and barley when Glyphosate was applied earlier than crop maturity; they did not report any data on the effects of the herbicide on weed control.

***Dry sowing*:** Sowing into a dry seedbed allows farmers to sow large areas with one seeder, but leads to a greater risk with weed control and little opportunity to apply knockdowns before seeding. For this reason dry sowing should not be used where weed seedbank numbers are high.

One possible technique to use in this situation is 'hair cutting', but this technique is not currently recommended. 'Hair cutting' involves spraying wheat at the half leaf stage with Spray Seed® with the intention of the wheat recovering and the weeds dying. For the technique to work grass weeds should be 1.5 leaf or greater and wheat should be half leaf or smaller (Newman and Adam 2002). The technique is one possible component of an integrated approach to lowering weed seedbanks, particularly where the grass weeds are resistant to in-crop herbicides.

Coating of seed to delay crop germination has been investigated (Reynolds *et al.* 2013). Retarding the crop germination relative to the germination of grass weeds aims to have the weed, say annual ryegrass, at the 1.5 leaf stage while the crop is only at half leaf stage. Wheat germination was reduced by both spraying (Newman and Adam 2002) and by applying the seed coat (Reynolds *et al.* 2013), but grain yield was unaffected with the lowest seed coat treatment or spraying (Newman and Adam 2002). Ryegrass control of 50% and wild radish control (sprayed at cotyledon stage) of 80% have been reported (Newman and Adam 2002).

3.9 Development of herbicide resistance in weeds

Conservation farming systems rely on herbicides to control weeds, and this has led to the evolution of herbicide-resistant weeds in Australian cropping areas. Herbicide resistance has been commonly recorded in annual ryegrass (*Lolium rigidum*), wild radish (*Raphanus raphanistrum*), wild oats (*Avena fatua*) and brome grass (*Bromus diandrus*). Broster and Pratley (2006) identified widespread herbicide resistance in annual ryegrass to a wide range of herbicide groups in the southern cropping areas. Resistance to group AI (diclofop-methyl, haloxyfop-R), group AII (clethodim, sethoxydim, tralkoxydim) and group B (chlorsulfuron, triasulfuron, imazapic/imazapyr) was common, particularly in Western Australia (Owen et al., 2007). Resistance to trifluralin (Group D) was relatively common in the eastern states (Figure 22), while resistance to simazine (1% of total samples) and glyphosate (0.4% of samples) has also been observed (Broster and Pratley 2006). Some populations of annual ryegrass had resistances to several herbicides (Broster and Pratley 2006; Owen *et al.* 2007).

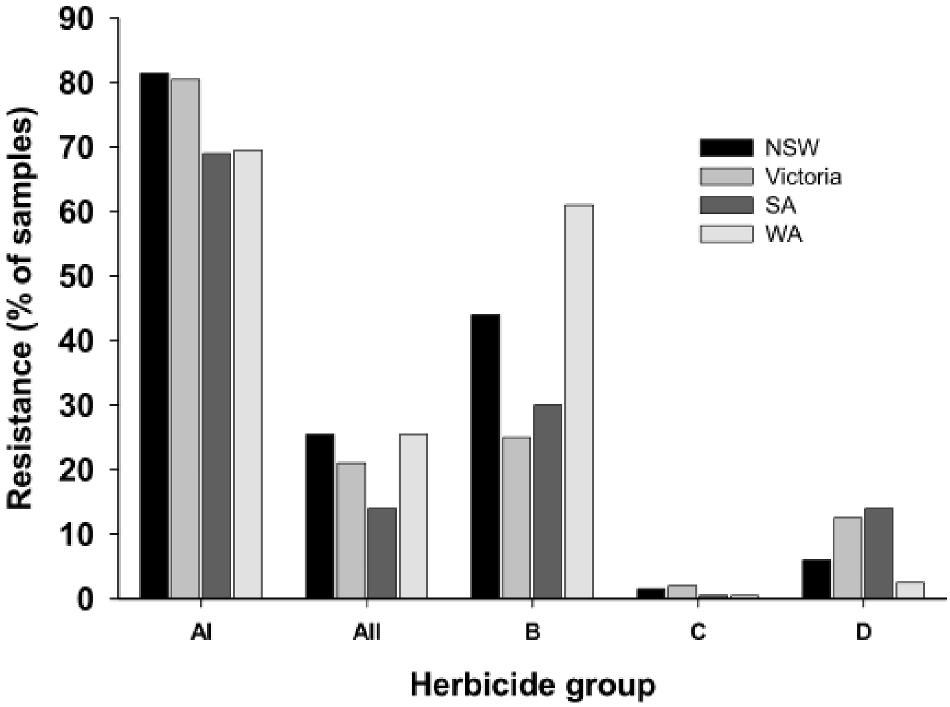

Figure 22. Frequency of resistance, in the southern cropping areas of Australia in annual ryegrass samples submitted by farmers, to five herbicide groups (from Broster and Pratley 2006), reprinted with permission[25].

Recent developments in herbicide resistance

Resistance to trifluralin and glyphosate continues to increase (Boutsalis *et al.* 2009). About 30% of southern Australian ryegrass populations are estimated to have some trifluralin resistance (Boutsalis *et al.* 2009). In 2013 there were 363 populations of annual ryegrass with glyphosate resistance (Figure 23), comprising NSW (116 populations), SA (149), Victoria (55) and WA (43). Glyphosate resistant populations of other weed species have been identified and include awnless barnyard grass, (*Echinochloa colona*) in 2007; liverseed grass, (*Urochloa panicoides*) in 2008; fleabane, (*Conyza bonariensis*) in 2010; windmill grass, (*Chloris truncata*) in 2010; and great brome, (*Bromus diandrus*) in 2011 (Preston 2013).

[25] ©CSIRO Publishing (2006), 24 October, 2013.

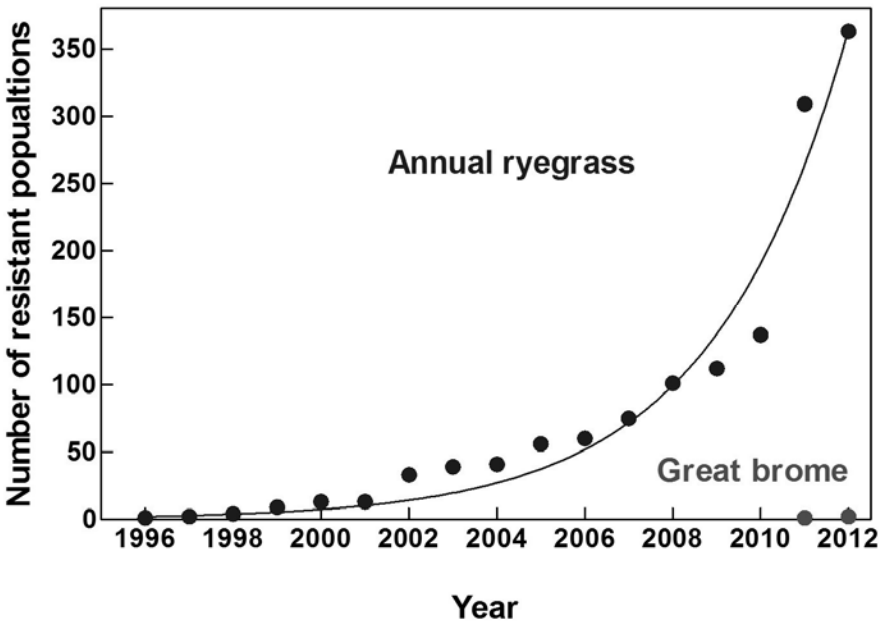

Figure 23. The increase in confirmed cases of glyphosate resistance in winter grass weeds between 1996 and 2012 (from Preston 2013), reprinted with permission[26].

Herbicide resistance is a global problem (Green 2013; Heap 2013). In the US the emergence of glyphosate resistance in weeds, particularly Palmer amaranth or Palmer pigweed (*Amaranthus palmeri*) has had a major impact. Glyphosate resistance was due to an over-reliance on glyphosate to control weeds and was particularly pronounced when 'Roundup Ready®' crops became available (Baldwin 2013). The use of a single herbicide (glyphosate) in both fallow and crop was simple and cost effective and other herbicides were displaced. The frequent use of glyphosate over a decade resulted in a major herbicide resistance problem "fields are overgrown and hand-weeding crews are common..." (Baldwin 2013).

Heap (2013) claimed that the three biggest herbicide resistance issues facing growers today were:
1. The rapid increase in the incidence of multiple-resistance in weeds that leave growers with few herbicidal options.
2. The over-reliance on glyphosate in Roundup Ready® cropping systems, resulting in a rapid increase in the number of glyphosate-resistant weeds.
3. The lack of new herbicide sites of action being brought to the market.

Extending the life of glyphosate before the development of glyphosate resistance would involve the use of other herbicide options and using non-chemical means of weed control.

Non-chemical control of weeds

Before herbicides were available to control weeds, growers in southern Australia relied on cultivation to control weeds pre-sowing. This reliance often resulted in late sowing as the earlier rains were employed to germinate weeds so they could be controlled by tillage. In-crop competition with weeds was enhanced by high crop sowing rates employed in earlier systems with narrower row spacings. Finally the burning of stubbles also contributed to weed

[26] Australian Glyphosate Sustainability Working Group, Australian Herbicide Resistance Institute (2013), 9 Oct 2013.

control destroying a portion of the seedbank. These practices are again being employed as part of an IWM system. Other options include hay making, green and brown manuring of paddocks by incorporating crops or spraying with non-selective herbicides before the seeding of weeds. Recently, systems of collecting weed seeds in the harvester and their destruction have been developed to further reduce the weed seedbank (Walsh *et al.* 2013).

Collecting weed seeds in the harvester relies on the weed seeds being held high enough to be harvested (Table 17; Figure 24). Fortunately many of the current major weeds of cereal crops fit this description. Walsh and Powles (2012) showed that a high percentage of total seed production was held at ≥15 cm height, a low harvester cutting height, at the time of maturity of a wheat crop (Table 17). Further, in their example, the seed was held in this position for four weeks; approximately the duration of harvest. Wild oats lost some seed from the seed head during the four week period (Figure 24).

Table 17. Percentage of total seed production retained above a low (15 cm) harvest cutting height at time of crop maturity (from Walsh and Powles 2012), reprinted with permission[27].

Species	Seed retention above 15cm % (range)
Annual ryegrass (*Lolium rigidum*)	88 (77-100)
Wild radish (*Raphanus raphanistrum*)	99 (95-100)
Brome grass (*Bromus diandrus*)	73 (61-95)
Wild oats (*Avena fatua*)	85 (73-100)

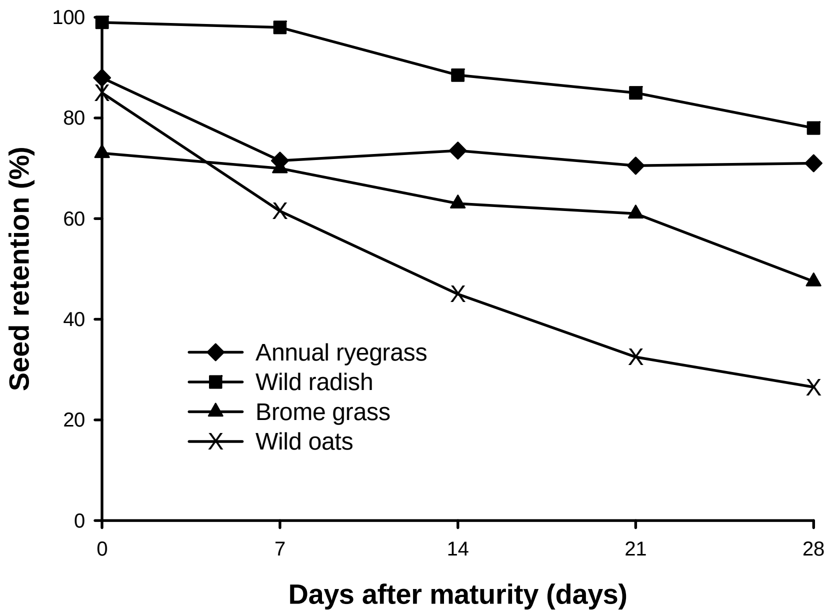

Figure 24. Retention of seed above 15 cm harvest height during the first four weeks of harvest for the major crop weeds of Western Australia (from Walsh and Powles 2012), reprinted with permission[28].

Harvested seed can subsequently be destroyed. The simplest method of destroying harvested weed seed is by narrow windrow burning. Narrow windrows are produced by fitting chutes to

[27] © Grains Research and Development Corporation (2012), 12 November, 2013.
[28] © Grains Research and Development Corporation (2012), 12 November, 2013.

the back of the harvester to produce windrows of chaff and straw 500 to 800 mm wide. These windrows are burnt in the following March-April (4 to 5 months after harvest) in preparation for sowing (Walsh and Newman 2007). Burning narrow windrows achieves higher temperatures for a longer duration than burning standing stubble or conventional windrows to more effectively destroy weed seeds (Figure 25). To prevent burning all stubble in a paddock this technique is usually limited to crops with a grain yield of 2.5 to 3 t/ha.

Chaff carts can also be used. In this system a cart is trailed by the harvester and collects the straw and chaff at the back of the harvester. The cart can be emptied on site to produce heaps of chaff for later burning, or harvester residues can be totally removed from the site (Walsh and Powles 2012). A system of baling the crop residue was also developed so weed seed could be removed from the site and the by-product had some value as a stock feed. (Walsh and Powles 2007; Walsh and Powles 2012).

The Harrington Seed Destructor® is an alternative trailing device which collects the chaff, containing the weed seeds, and destroys the seed by using a milling cage, then deposits the residue back into the paddock (Walsh *et al.* 2012). More recent developments include incorporating the cage mill system within the harvester (Anon 2013b), or replacing the system of weed seed destruction with microwave destruction (Faulkner 2011).

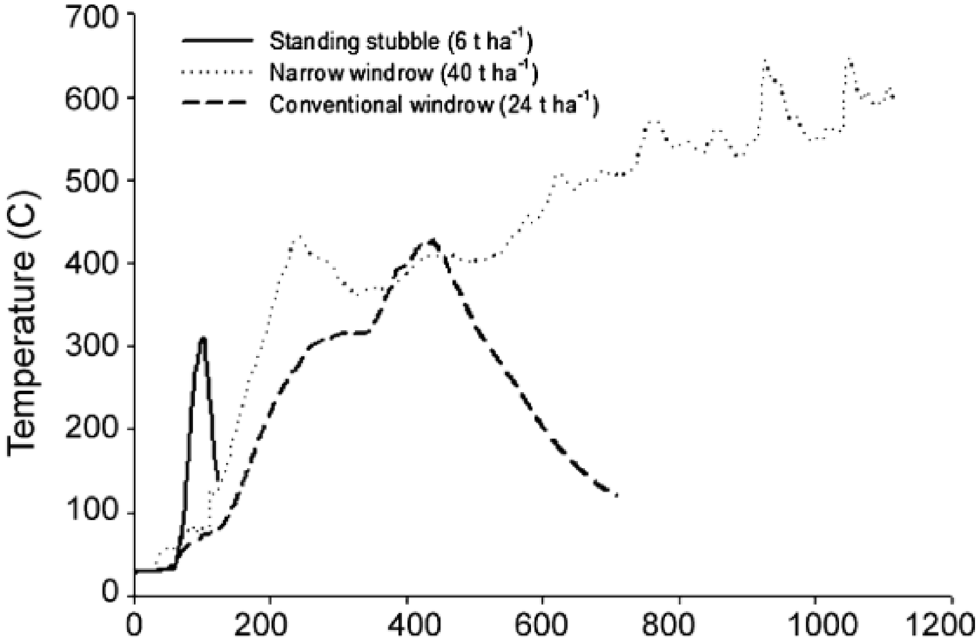

Figure 25. Average temperatures at five second intervals during burning of standing wheat stubble, stubble in conventional windrows and stubble in narrow windrows (from Walsh and Newman 2007), reprinted with permission[29].

In practice all three post-harvest systems are comparably effective on ryegrass, if they are executed well (Table 18). Walsh (2012) found no differences in efficacy on average in WA with ryegrass across 12 sites, while Aves and Walsh (2013) had a similar result across 14 sites in south-eastern Australia.

[29] © Elsevier (2007), 14 October, 2013.

Table 18. The effect of harvest and post-harvest treatments on ryegrass emergence during the following autumn in the southern cropping areas of Australia.

Treatment	Reduction in emergence of annual ryegrass (%) Average of 12 sites across WA (Walsh 2012)	Average of 14 sites across south-eastern Australia (Aves and Walsh 2013)
Harrington Seed Destructor®	56	55
Chaff cart	57	55
Narrow windrow burning	58	55
LSD (P=0.05)	ns	ns

All three systems were developed in WA and are increasing in adoption. Fifty percent of growers in WA were practicing windrow burning, and 75% were practicing some form of management of weed seeds at harvest, or planning to do so (Peltzer 2011). There is a low rate of adoption of these non-chemical systems in south-eastern Australia, despite their apparent usefulness in extending the life of herbicides, and some concerns as to their applicability (Street and Shepherd 2013). The key concerns with the most obvious method (windrow burning) are that:

- The stubble yields in eastern Australia may be higher than is common in WA, and as a result it may be difficult to burn the windrow without the fire burning the entire paddock.
- Summer rainfall (more common in the equi-seasonal rainfall of central and southern NSW) could reduce the effectiveness of the burn by compacting and wetting the narrow windrow.

More broadly, these systems rely on being able to collect a large proportion of weed seed by harvesting with a low harvest height. This tactic would not be realistic on rocky or sloping ground. There is also the suggestion that selection may be applied over time to the weed population for weeds to drop seed by harvest. Adaptations such as earlier maturity of the weeds and enhanced abscission could occur. Some weeds would not be candidates for this system as their seed is small and light and could not be successfully harvested (for example, flaxleaf fleabane (*Conyza bonariensis*) and sowthistle (*Sonchus* spp.)).

An alternative system is in early development which uses microwaves to destroy weeds (Brodie *et al.* 2012b; Brodie *et al.* 2012a; Anon 2013a). While this system would have a high energy input, compared with the total energy input into herbicide applications, there is scope to potentially reduce the energy requirement. Microwaving the soil surface could destroy weed seeds on the soil surface in undisturbed fallows or in the inter-row space of wide row crops, but the destruction of buried weed seeds by microwaving the surface soil to 5 cm depth is not viable.

Non-chemical methods of weed control are not only alternatives to herbicidal control but could be used in conjunction with herbicides to more rapidly gain control of the weed seedbank and to lengthen the useful life of herbicides.

3.10 Strategic tillage within a conservation farming system

Conservation farming involves no tillage and full stubble retention. However, the sustained use of no-till can create problems in some situations. The occasional use of tillage would appear to address many of these problems. Strategic tillage could have a place in conservation farming systems to ameliorate the effects of no-tillage including stratification of nutrients, inability to incorporate lime and herbicides, increased pest populations, inability to manage herbicide-resistant weeds, increased disease incidence, consecutive high stubble loads and compaction by livestock in mixed farming systems (Conyers 2013). However, the concern is that the benefits of no-till are cumulative, and a single cultivation could destroy these benefits.

Problems with sustained no-till

Some soils acidify under agriculture and require amendment with lime (see Upjohn *et al.* 2005). With no-till there can be a layer at 5-10 cm depth which becomes very acidic (Conyers *et al.* 1996), but is ameliorated by tillage and lime incorporation. In addition the acidification of the surface 0-10 cm layer appeared to be more pronounced when stubble was retained (Heenan and Conyers 2000). Applied lime was most effective when incorporated and mixed into the soil (Scott and Coombes 2006), and when applied on the soil surface in a no-till system was slow to move through the soil profile (Conyers *et al.* 2003).

Nutrients in the soil such as P, manganese (Mn), copper (Cu) and zinc (Zn), stratify in the soil under no-till, accumulating in the surface soil. Plants move these nutrients to the soil surface in plant litter, but as they are immobile in most soils they are not moved downwards in the soil by leaching. Organic matter also accumulates in the few centimetres of the soil surface. Under dry conditions the resulting dry soil surface may limit the availability of P to the plant and also slow or stop breakdown of the organic matter and limit N availability to the crop. Asghar *et al.* (1996) conducted a single cultivation to 10 cm depth in an eight year no-till system, where P, K and Zn were stratified at the soil surface (Table 19). Phosphorus and potassium were evenly distributed in the 0-10 cm soil layer after cultivation to that depth. Increased uptake by wheat of P, K and S was reported, despite a decrease in vesicular-arbuscular mycorrhiza, and an increase in grain yield (28%) in the first crop following cultivation, when compared with maintaining no-till. These results suggest that the practice of occasional cultivation in no-till systems may need to be accepted as part of 'conservation tillage'.

Table 19. Soil characteristics and effect of soil mixing (0-10cm) on distribution of phosphorus and potassium (from Asghar *et al.* 1996), reprinted with permission[30].

Undisturbed soil							55 days after rotary hoeing to 10 cm depth	
Soil depth (cm)	pH(1:5)	Organic C (%)	Total N (%)	DTPA-Zn (mg/kg)	Colwell P (mg/kg)	Replaceable K (cmol(+)/kg)	Colwell P (mg/kg)	Replaceable K (cmol(+)/kg)
0-5	7.3	1.40	0.080	0.097	47.2	0.94	38.7	0.76
5-10	7.4	1.23	0.073	0.77	27.6	0.55	36.7	0.72
10-15	7.1	0.80	0.050	0.47	16.3	0.35	20.8	0.42
15-20	7.1	0.73	0.043	0.43	10.7	0.25	12.0	0.27

[30] © Australian Society of Agronomy (1996), 8 October, 2013.

An elevated P concentration in the soil surface may increase P in runoff under no-till (Quincke *et al.* 2007), since dissolved phosphorus in the runoff replaced particulate P from eroding soil. A 'one time' tillage operation could be a possible solution.

There is also a suggestion of lateral stratification of immobile nutrients in the soils. Bolland and Brennan (2006) suggested that applied P, Cu and Zn in no-till systems would remain at the site of the fertiliser band and may be less effective as residual fertilisers for subsequent crops. They suggested cultivation every five to seven years to mix the soil surface layer as a means of making the residual P, Cu and Zn more plant available for the cultivated crop, and any subsequent no-till crops. In their experiments (46 experiments across 16 sites with many drought affected), yields of grain were generally higher where the soil had been cultivated prior to sowing, compared with maintaining a direct-drilled sowing regime. However, this advantage did not appear to be due to increased availability of P, Cu or Zn because a response to application of these nutrients occurred at only one site.

Under no-till diseases caused by *Rhizoctonia* (Roget 1995; Gupta *et al.* 2010) and *Pseudomonas* (Kirkegaard *et al.* 2001; Simpfendorfer *et al.* 2001, 2002) around the roots of some species and cultivars can damage crops. These diseases can be reduced through cultivation (Simpfendorfer *et al.* 2002; Anon 2008a).

Cultivation is frequently recommended as part of integrated weed management, particularly to manage herbicide resistance in weeds (see McGillian and Storrie 2006). Cultivation aims to kill growing weeds (Peltzer undated), or to bury weed seeds by soil inversion (Cheam and Lee 2009; Peltzer and Newman undated). Burial of seeds is most effective with annual grass weeds, which have low seed dormancy, and is less effective with broadleaf weeds such as doublegee (*Emex australis*) and wild radish (Table 20).

Table 20. Seed survival of four major crop weeds in the WA wheatbelt after four or five years (wild radish data only) of shallow and deep burial. The data for wild radish are the mean across two sites, but data for the other species are the mean across three sites (from Cheam and Lee 2009), reprinted with permission[31]

	Viable seeds remaining (%) at three burial depths		
Species	0 cm	1 cm	15 cm
Annual ryegrass	0.6	0.9	0
Brome grass	0	0	0
Doublegee	21.0	10.5	18.3
Wild radish	0	0	33.0

In mixed farming systems, grazing during the pasture phase can be used to minimise weed burdens but infiltration of rain can be slowed following compaction by livestock. Tillage might be necessary to improve infiltration of rain. In central and southern NSW the most likely time for tillage to occur is as a paddock returns from pasture to crop, and this is the time the opportunity is taken to apply lime as it will be incorporated by cultivation.

Additionally, conventional tillage in dry soil has been found to suppress root lesion nematode (*Pratylenchus* spp) populations when compared with direct drilling (Anon 2006, 2009a), but is damaging to soil. By contrast, Cereal cyst nematode damage appears to be reduced with no-till systems (Anon 2009a).

[31] ©Department of Agriculture and Food WA, (2009), 12 November, 2013.

Cultivation can reduce slug and snail numbers (Leonard 2003; Nash 2012) and can be used to lower numbers of snails and slugs before canola crops. Cultivation has been suggested as a way of reducing numbers of mice, by destroying habitat and partially burying food supply (Brown 2002; Anon 2011a). Possible increase in soil organic carbon has been proposed by the addition of nutrients and the incorporation of stubble by cultivation

Incorporation of stubble was not as damaging to soil organic carbon as burning of stubble and cultivation (Kirkby 2003), and with the supply of additional nutrients stubble incorporation may increase soil organic carbon (Conyers 2012).

Research in 'one time' tillage

Grandy *et al.* (2006) opined that "Without permanence, many of the agronomic and environmental benefits of no-till are simply not realised" and that "years of soil regeneration can be lost to a single tillage event". Grandy *et al.* (2006) found that cultivation caused significant and rapid reduction in soil aggregation, protection of light fraction (LF) carbon and soil organic matter due to mineralisation. These effects were studied in the short term, and the tillage was repeated annually. The suggestion that a single tillage in an otherwise no-till system was a negative was supported by Bruggink (2008) and the potential benefits of tillage were regarded as small compared with the disadvantages.

Baan *et al.* (2009), in three experiments of three years duration in Canada, found little effect of a single tillage operation in no-till farming systems on soil properties and crop growth. Soil organic carbon, pH, aggregation and water content were unaffected. Bulk density (5-10 cm) and P stratification decreased. Grain yields of wheat and canola were not affected in any of the three years following tillage, except at one site where yield of canola was reduced by some cultivation treatments in the first year of the experiment. This was thought to be due to nitrogen immobilisation. The results indicate that several years of tillage would be required to significantly impair soil properties.

Quincke *et al.* (2007) also found one-time tillage had no effect on yield or soil aggregate stability, but tillage reduced P loss (runoff). Wortmann *et al.* (2010) concluded that one-time tillage had no significant effect, positive or negative, on long-term yield, soil aggregation, stratification of soil P, SOC, bulk density or soil microbial biomass, with values measured five years post-cultivation similar to that of long-term no-till treatments.

Pierce *et al.* (1994) working in corn cropping in Michigan, US, found a single cultivation of a previously no-till soil created soil properties similar to conventional tillage in that year. However, after one year they were between no-till and conventional tillage, and had largely disappeared after 4-5 years. Tillage decreased bulk density and increased total porosity to levels equal to conventional tillage, and redistributed surface P, K and SOC within the surface 20 cm, residual effects were present one year after tillage, but not after 4-5 years. Nitrogen mineralisation was higher after ploughing than in no-till after one year. However, the C and N in the soil surface (0-50 cm) remained lower in the cultivated treatment than in the continuous no-till plots after 4-5 years.

The impact of a one-time tillage operation on soil properties and productivity in an otherwise no-till system in Australia is uncertain. Neither of the Australian studies (Asghar *et al.* 1996; Bolland and Brennan 2006) continued into the following years to study the longer term effects of this interruption to the conservation farming system.

A GRDC project is currently underway to address the mixed messages farmers are receiving regarding the use of tillage in conservation farming systems. It is aiming to evaluate the impact of a single strategic cultivation on soil chemical, physical and biological properties and the time taken for the soil to recover from any detrimental effects (Conyers 2013; Dang *et al.* 2013). However at the time of writing, experiments established in the projects have results for only one season.

One year of cultivation in long-term no-till paddocks in Queensland and northern NSW reduced weed densities at all sites, decreased soil bulk density (although not significantly) at all except one site, decreased the SOC mass at two of the five sites, reduced available phosphorus (0-10 cm) at all sites (significantly at only two sites), significantly increased soil microbial activity at one site and decreased it at another (no effect at other sites) (Dang *et al.* 2013). Cultivation did not affect soil moisture at sowing at three sites, but was lower at two sites: the first had little rainfall between cultivation and sowing and the second has a high clay content soil requiring more rainfall to replenish soil moisture (Dang *et al.* 2013). These findings indicate that the timing of tillage and the seasonal conditions should be considerations before strategic tillage (Dang *et al.* 2013). The adverse effects of cultivation do not necessarily translate into losses in productivity or profit with yield increases at all sites (significantly at only one site) and profitability increased by $2.50-$35.80 per hectare in the first year after cultivation (Dang *et al.* 2013).

4. CONCLUSION AND GAPS

During this review of literature and research on stubble retention in southern Australia several research, development and extension gaps were identified. These gaps are likely to limit further adoption of stubble retention and threaten the sustainability of stubble retained systems. Identification of the gaps is important for directing future RD&E to improve efficiencies and achieve the most robust and useful outcomes from investment. Following is an outline of the gaps identified.

The structure and quantity of stubble

The structure (architecture) and quantity of various crop stubbles required to maximise benefits from stubble retention have not yet been determined. This knowledge is a prime managerial requirement to drive stubble management decisions.

Blockages at sowing remain an issue and growers need to be aware of management options available and their reliability in reducing stubble amounts or making the stubble load manageable for sowing machinery. Growers also need to consider accumulation of stubbles over two seasons in dry conditions. As there are growers experienced in stubble retention systems it is likely that the required knowledge is available. Additionally, there is scope to develop a decision aid (USB stick, smart phone app) to assist with estimating stubble load and making decisions to manage that stubble (cutting height at harvest, post-harvest management).

There is a lack of knowledge on the stubble quantity required to maximise moisture retention, and if the stubble should be flattened or left standing. Experience in the US indicates that the stubble arrangement has a substantial influence on moisture retention (Smika 1983), but limited Australian data indicates that stubble arrangement is of little consequence (Browne *et al.* 2012; Sadras *et al.* 2012). The leading questions are ‘when are stubbles likely to retain moisture for use by the following crop’ and ‘how much stubble is required at that time’.

Recent findings indicate that stubble has the greatest impact on accruing stored soil moisture in autumn and into winter when the newly establishing crop is present rather than over the summer period. The benefit of maintaining some surface moisture through stubble mulching so that early sowing is possible is traded against the cost of poor emergence if mulch is not evenly spread (especially with canola). Weed control in summer fallow is of major importance for conserving moisture for following crops.

Crop establishment

Establishing crops in retained stubble remains a concern for growers, particularly establishing canola in cereal stubble. Growers have shown great interest in inter-row sowing. The issues with inter-row sowing are the reliability of plant establishment and accuracy of seed placement using a range of sowing and guidance equipment. The capacity of inter-row sowing to operate effectively and reliably with heavy stubble loads is unresolved. Inter-row sowing has mainly been associated with controlled traffic farming (CTF) systems and most farmers have been reluctant to fully adopt this system. CTF systems with no livestock do not suit the majority who are mixed farmers. The costs and technology requirement for setting up 2 cm accuracy with GPS guidance is an impediment. Leaving stubble standing also has the issue of stubble rotting off at the base in wet summers which then causes problems at sowing.

Weed control

Weed control in stubble retained systems is an issue due to the reduced herbicide performance. This can be the result of stubble intercepting sprayed herbicide or the increase of herbicide resistant weeds. Manufacturers' guidelines for pre-emergent herbicides often state that stubble ground cover should not be greater than 50% which is inconsistent with current commercial application of these chemicals. There are also suggestions of withdrawing registration of some herbicides (for example, triazines). Increased reliance on herbicides has contributed to trifluralin and glyphosate resistance. This has focused attention on non-chemical weed control and integrated weed management aimed at lowering the weed seedbank. An integrated approach can embrace cultivation, stubble burning, or in-crop competition using higher sowing rates. The seedbank of crop weeds can be reduced by hay making green or brown manuring or by reverting to a pasture phase.

The collection and destruction of weed seed at harvest has been developed in WA and, potentially, is under-applied in the GRDC southern region. Barriers to weed seed harvesting in eastern Australia include the recommended low harvest height (15 cm) which poses problems on uneven ground and in heavier yielding crops where it slows harvest operations. The height of the weed seed at maturity also presents an issue as it could vary across cropping systems/agro-ecological zones and depend on variety, row arrangement and density of crop plants. Further concerns are that in heavy stubbles, fire used to destroy seed in the narrow windrows or chaff cart heaps when they are burnt in autumn/early winter, may escape into the general paddock. Also the equi-seasonal rainfall in central and southern NSW, and north eastern Victoria with its summer rain, may compress and dampen the narrow windrow or chaff cart heap and prevent a successful hot burn.

Yellow Leaf Spot

Yellow leaf spot remains an anomalous disease in the southern region. It is widespread in stubble retained cropping systems but is ranked as far less significant a disease causing yield loss in this region than in the Northern or Western regions. However, most of the available data were collected up to 2008 (Murray and Brennan 2009) after a series of below average rainfall seasons. In wetter seasons, the disease is present and is frequently sprayed with fungicide. There is uncertainty about the identification of yellow spot in the field (any 'yellow leaf spot' is blamed on the disease) and there is a perceived need to educate and support advisory agronomists in disease identification. Spraying is advised to protect the flag and previous leaf, therefore it is likely that much spraying is too early to benefit grain yield.

Pests
Invertebrate and vertebrate pests are associated with retained stubble. These pests include snails and slugs, in addition to mice, with the more recent emergence of earwigs, slaters and weevils. Research is in the early stages for many of the emerging pests, while recognised pests (snails and slugs) may be expanding their geographic distributions and importance. Many of these vertebrate biota feed on decaying plant material and then move onto emerging crops. Burning, rather than retaining stubbles, has been recognised as the main historical control method.

Soil Organic Carbon and nutrients
The benefit of long-term stubble retention on SOC has been extensively researched. Although modelling outputs claim improved SOC from stubble retention, measurements suggest that SOC is either slightly increased or unchanged by stubble retention compared with stubble burning at rainfalls common in the Australian wheat belt. The soil friability and rainfall infiltration changes observed by farmers are due substantially to the redistribution of SOC in the soil profile. SOC accumulates in the shallow soil surface and affects soil surface characteristics. Recently, stubble incorporation and the addition of N, P and S nutrients have been suggested to increase SOC, but the effect of repeated soil disturbance and mixing of SOC and nutrients has not been considered. Additionally, the conservation of nutrients (N, P, S) under stubble retention systems, compared to their loss through burning of stubbles, is not clear. Lower fertiliser requirements in stubble retained systems is undemonstrated.

Cost//benefit analysis
Cost/benefit information is required for the overall stubble retention system and its component parts. The overall system involves complex decisions and the off-setting of disparate components. For example, wide rows in wheat crops have a yield penalty compared to narrow rows. However, widening rows is a component of making the stubble retention system operate, from which other benefits accrue. At a simpler level, the decision to use a low cutting height at harvest can be compared to using a normal cutting height, and follow with a stubble cut post-harvest. The costs of slowing harvest and increased machinery wear, fuel use and man hours at harvest can be costed and compared with the post-harvest operation. The risk of rainfall interfering with harvest and lowering grain quality is far more pressing in large parts of the southern region (central and southern NSW and north eastern Victoria) than in strongly Mediterranean climates with a low chance of rainfall at harvest.

Questions remaining on the integration of livestock in stubble retention systems include; 'what is the cost/benefit of livestock considering the direct and indirect effects of livestock in the mixed farming system?'; 'what are the effects of livestock grazing stubbles and the implications for sowing difficulties into trampled stubble?'; and 'do the benefits of this limited grazing resource make up for the extra management required to successfully sow the following crop?'

5. APPENDICES

Appendix 1. Summary of key details and findings of studies of growers in southern NSW.

Reference	Location and Participants	Key results
Burns *et al*. (2010) Graham Centre Stubble Forum	• Southern Slopes & Riverina of NSW • 44 growers, advisors and researchers	• Diversity of stubble retention systems • Forward planning, monitoring and flexibility are key to sustainability with a focus on disease and weed management • Stubble management begins at harvest • Need benefit/cost analysis of livestock in system • Fate of nutrients in stubble retention systems is unclear • Lack guidelines on quantity and architecture/form of stubble to optimise benefits: soil protection, moisture accumulation, stubble breakdown • Limited understanding of impact of stubble retention on invertebrate populations
Burns *et al.* (2013) Stubble retention - grower response to contrasting seasonal conditions: 2010 and 2011	• Southern Slopes & Riverina of NSW • 15 selected growers, with recognised experience and/or commitment to full stubble retention • Mixed farming and continuous cropping systems.	A shift in seasonal conditions required adjustments to management and highlighted the importance of: •Management of stubble from harvest-low cutting height and effective spread of chaff behind header •Timely weed control from crop maturity to sowing next season crop •Diversity of rotation and variety selection to minimise disease and weed pressure
Davis (2006) Dryland farming systems survey	• Dryland cropping zone of the lower and mid Murrumbidgee Catchment, NSW • 700 respondents to mail-out survey	• Main reasons for retaining stubble are: (1) conserve soil moisture; (2) increase soil organic matter levels; (3) improve soil structure; (4) protect soil. • High stubble loads is the reason most growers give for reducing stubble loads; grazing and/or burning are the strategies most commonly used to reduce stubble load • Other reasons for reducing stubble loads are to aid weed and disease management or to improve efficacy of pre-emergent herbicides • Burning of stubble usually occurs one to four weeks prior to sowing
Holding (2010) Cereal Stubble Management on-farm demonstrations and case studies	• Southern Slopes & Riverina of NSW • 15 case study farms • Growers with significant experience in full stubble retention • Mixed farming and continuous cropping systems.	• Management of high stubble loads a feature of all except the western Mirrool Creek sites that had minimal stubble loads during the prolonged Millennium Drought • Perceived benefits of full stubble retention included soil protection, improved soil structure, increased soil organic carbon levels improved moisture storage The demonstration sites highlighted: • Reducing harvest height will aid trash flow through seeding equipment • Large variation in spread of chaff behind headers • Concentration of chaff and crop residues in header trails identified as an issue at sites with long-term use of GPS on set paths • Plant establishment in header trails is affected if straw spreaders are ineffective
Koen (2005) Cereal Stubble Management Project survey	• Harden Murrumburrah, NSW • Mixed farming, high rainfall area with high stubble loads in most seasons • 42 respondents – self-selected with a demonstrated interest in the local stubble management project	• Majority of growers use a combination of stubble treatments: 83% burn a proportion; 79% rely on grazing to reduce stubble loads and only 19% indicated they retain a proportion of their stubble intact. • Reasons for retaining stubble: (1) ground cover / prevent wind & water erosion; (2) prevent nutrient loss; (3) increase soil organic matter content; (4) stock feed; (5) minimise air pollution (6) moisture conservation • Reasons for burning stubble: (1) too thick or tangled to sow through in some years; (2) disease control; (3) weed management; (4) pre-emergent herbicide efficacy; (5) ease of management

Appendix 2. Summary of key details and results of stubble grazing experiments in the south eastern Australian grain areas.

Site/s(year/s)	**Treatments**	**Key results**	**Comments**	**Reference**
Ultima, Mallee Victoria and Banyena, Wimmera Victoria (2011)	1. Control 2. Grazed (light-moderate)	- Slight increase in surface bulk density. - No measurable differences in soil surface aggregation, soil water, weed seed burial. - Increases in nitrogen were observed but did not impact on crop growth or yield. - No significant impact on subsequent crop yield (decreased 1% at Banyena; increased 2.02% at Ultima).	Light to moderate grazing does affect soil properties but shows no impact on subsequent crop growth and yield.	Jones and Ferrier (2011)
Hopetoun, Mallee Victoria and Quantong, Wimmera Vitoria (2012)	1. Control 2. Grazed (light-moderate)	- No measurable differences in surface bulk density, soil surface aggregation, soil water, weed seed burial or soil nitrogen. - No significant impact on subsequent crop yield (decreased 2.86% at Hopetoun and increased 4.28% at Quantong).	Light to moderate grazing does affect soil properties but shows no impact on subsequent crop growth and yield.	Jones and Ferrier (2012)
Greenethorpe, NSW and Tootool, NSW (2008)	1. Control 2. Grazed (light-moderate)	- Grazing led to increases in soil bulk density and soil strength and decreases in water infiltration. - The effects of grazing did not significantly influence stored moisture at sowing, crop establishment, crop growth or subsequent crop yield (increased 5% at Greenethorpe and no change at Tootool).	Livestock can degrade soil surface physical properties but unless severe, have little impact on the subsequent crop. Concern over impacts of grazing is unwarranted.	Bell *et al.* (2011)
Temora, NSW (2009 to March 2010)	1. Nil graze, stubble retention 2. Nil graze, stubble burn 3. Stubble graze, stubble retention 4. Stubble graze, stubble burn 5. Winter graze, stubble graze, stubble retention 6. Winter graze, stubble graze, stubble burn	- Grazing reduced water stored at depth as a result of reduced infiltration and increased raindrop impact damage. - No differences in surface soil water - No significant difference in yield of subsequent canola crop (increased 2.44%)	Soil physical effects from grazing are shallow and transient and rarely affect subsequent crop yield if grazing and groundcover guidelines are followed.	Hunt *et al.* (2011).
Temora, NSW (2010 to 2012)	As above	- Plant available water at sowing was higher in ungrazed treatments, due to deep stored moisture during the 2009-2010 fallow and less soil evaporation following frequent rainfall events.	Stubble can significantly improve infiltration and reduce evaporation if a minimum 2 t/ha stubble is retained or 70% groundcover maintained.	Fettell *et al.* (2011) Hunt *et al.* (2012a)
Condobolin, NSW (2009 to 2012)	1. Added stubble 2. Ungrazed 3. Moderate graze 4. Heavy graze	- No significant difference in soil moisture storage between treatments - No yield difference between the ungrazed and light-moderately grazed treatments - Significant yield losses of up to 6.78% occurred in heavily grazed treatment.	Heavy grazing of stubble can significantly decrease yield of subsequent crops however light grazing has no significant impact compared to the nil graze treatment.	Fettell *et al.* (2011) Hunt *et al.* (2012a)

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