Stubble Retention in Cropping Systems in Southern Australia: Benefits and Challenges

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FORWARD

Welcome to the EH Graham Centre Monograph, the first in a series from the EH Graham Centre for Agricultural Innovation (an alliance between Industry & Investment NSW and Charles Sturt University). The aim of this Monograph series is to provide an in-depth review of topics relevant to agricultural systems in southern Australia, identifying opportunities and challenges for research and implementation of research in the area.

The EH Graham Centre aims to be the Australian centre of excellence in mixed farming systems research, undertaking world class collaborative research and education to deliver productivity efficiency and growth to address the challenges of food security, climate change, water scarcity, bio-security and skills shortages in agriculture. One of the key strategic research initiatives of the Centre is the "Conservation Farming and Stubble Management" initiative, which examines soil carbon and nutrient use efficiency together with air and water quality.

The first EH Graham Centre Monograph "Stubble Retention in Cropping Systems in Southern Australia: Benefits and Challenges" examines the positive and negative outcomes from the adoption of stubble retention in south-eastern Australia. The Monograph focuses on issues of stubble retention in a changing climate, where adaption to change and maintaining ground cover are increasingly important.

Now is an important time to review research into stubble retention given rapid advances in agronomy and crop management over the last 10 years. We aim to identify opportunities to build on past research and deliver new directions for research into stubble retention.

The financial support from the Grains Research and Development Corporation to cover printing of Monograph No.1 is gratefully acknowledged.

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

Professor Deirdre Lemerle
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Helen Burns and Edward Clayton
Editors

SUMMARY

Late stubble burning just prior to sowing is commonly practised in the south-eastern cropping areas of Australia which includes central and southern New South Wales (NSW), Victoria and South Australia (SA). However, stubble burning may be prohibited due to the perceived risks to public health from smoke. Regional information from southern Australia was reviewed in order to identify the basis for non adoption of stubble retention in central and southern NSW. We sought to highlight any gaps in knowledge of stubble retention practice, and impacts which may contribute to non adoption.

In the current monograph, "stubble retention" implies standing stubble or surface-applied stubble/mulch, and incorporated or buried stubble is rarely discussed. Similarly, stubble retention was separated from tillage practice, with direct drilling and/or no-tillage as the most relevant context for stubble retention

In Western Australia (WA), the high level of adoption of stubble retention may have resulted from the risk of wind erosion on sandy soils, with the relatively low stubble loads not presenting a barrier to adoption. Similarly in Queensland and northern NSW, the intense summer rainfall and its associated soil erosion risk have contributed to the retention of crop stubble as the dominant practice. In contrast, erosion risks from water and wind have been lower in central and southern NSW and risk of erosive summer rainfall was very low in Victoria and SA. Furthermore, the later burning of large stubble loads just before sowing practised in southern Australia, had some characteristics of stubble retention, by maintaining stubble during much of the summer/autumn period. The time of critical risk was after late stubble burning in March/April, when the soil surface was briefly exposed, and before the establishment of some ground protection, usually by early winter (June/July).

The presence of stubble can increase water infiltration and slow moisture losses through evaporation, increasing soil moisture storage at sowing. These effects appear to be of most value in Queensland and northern NSW, where production of winter cereal crops is highly reliant on stored soil moisture, but likely to be of less importance in the more southerly cropping areas where winter crops are more dependent on incident rainfall. In central and southern NSW there is a component of summer rainfall, which could be stored in the soil and be of benefit to a subsequent crop, particularly in lower rainfall years or environments. The effect of late stubble burning (compared with retention) on stored soil moisture is unclear.

In dryland crops, burning of stubble causes losses of approximately 4 kg nitrogen/t of wheaten stubble burnt; with average losses of 15-26 kg/ha of nitrogen (N) in high-yielding areas. These losses were less than suggested previously. Further, in stubble-retained systems, N may be immobilised. While immobilisation rates of 5-13 kg/ha of N with the decomposition of 1 t/ha of wheaten stubble can be derived from European research, the optimal rate of N fertiliser was only increased slightly by stubble incorporation in WA.

Soil organic carbon (SOC) was less in stubble-burnt or stubble-removed systems than in stubble-retained systems. However, there was no evidence of sequestering of C in stubble-retained systems; rather the amount of SOC in the soil declined at a slower rate with stubble retention compared with stubble burning in cropping systems. Where stubble retention was practised, SOC was greater in the shallow surface soil (0-5 cm) than when stubble was burnt. This increase in SOC may contribute to greater structural stability and water infiltration in the soil surface and greater earthworm populations.

Blockages of sowing implements by stubble were the primary reason for non adoption of stubble retention by farmers in southern and central NSW, where stubble loads were high. Traditional sowing machinery was limited to sowing through 2-3 t/ha of cereal stubble and modification of machinery combined with pre-treatment of stubble (slashing, harrowing) can enable sowing to be conducted through 4-5 t/ha stubble. Heavier stubble, typical of the eastern higher rainfall areas of central and southern NSW, would require the purchase of specialist machinery. Widening sowing rows in cereals, which reduces stubble blockage problems, is likely to reduce cereal yield.

Estimates from field reports indicate that 20-49% of the stubble quantity at harvest is decomposed and lost by the time of sowing in southern Australia, compared with 57-84% in Queensland, where higher rainfall in summer would hasten decomposition of stubble.

Burning stubble, rather than its retention, reduced the carry over of diseases and pests to subsequent sensitive crops. The temperatures achieved in a stubble fire influence the effectiveness of the fire in controlling some plant disease on the stubble and Australian field examples of the effectiveness of stubble burning in the control of crown rot, common root rot, eyespot and yellow spot are presented. Similarly, stubble retention increased the populations of some grasses in subsequent crops.

Conservation farming systems with stubble retention relied on herbicide use for weed control and this has led to a problem with herbicide resistant weeds, particularly annual ryegrass, wild oats and wild radish. The integrated management recommended for control of resistant weeds included a reversion to stubble burning and cultivation.

Acidification of the surface soil (0-10 cm) was greater with stubble retention than stubble burning, in both southern NSW and SA. The effect was confined to the shallow surface soil (0-5 cm). Some nutrients (P, Zn, Cu) accumulated in the soil surface under conservation tillage. Stubble retention may contribute to the stratification and increased fertiliser input or occasional cultivation were suggested as amendments. Similarly stratification of soil pH can be amended by the addition of lime and its incorporation through cultivation.

Stubble retention is claimed to increase cereal yield in some areas. The evidence reviewed in the current monograph, however, indicated that yield was not significantly improved with stubble retention compared with stubble burning or stubble removal and yield may frequently be lower with stubble retention. In most experiments, the small yield loss was not related to seasonal rainfall, but in a few experiments, the adverse effect on yield of stubble retention was greater in wetter seasons. This effect of growing season rainfall needs to be understood as yield reductions with stubble retention were high (up to about 1 t/ha of grain) in seasons of high potential yield.

The results of long-term experiments do not always predict the outcomes in commercial agriculture. Limitations were imposed on long-term experiments which were not important or not relevant to farming. Stubble retention may provide an earlier sowing opportunity than stubble burning due to preservation of soil moisture in the soil surface and this effect would not be accounted for in experiments sown on the same day, or over a few days. Also, in many areas of Australia, a pasture phase was typical of the farming system, but most experiments and/or treatments related to continuous cropping. Thus, the frequency of stubble burning in experiments was often far higher (every year), than would be observed in commercial agriculture. Any advantage or disadvantage of stubble burning may be over represented in the experimental results.

There appeared to be scope for breeding wheat better adapted to stubble retention systems. Sources of disease resistance had been identified and applied breeding is required. Longer coleoptile wheats were identified and they minimised the consequences of poor depth control at sowing, and assisted emergence through stubble. In the longer term, the competitive ability of wheat may be enhanced and specific allelopathic characteristics may be identified and incorporated into new cereal cultivars.

Research examining systems maintained in long-term conservation farming in which the system is “disturbed” by infrequent cultivation and/or stubble burning is required. These practices appeared necessary to control weeds, mix the surface soil to de-stratify nutrients and incorporate lime in acidifying soils. If the benefits of conservation tillage accumulate in the longer term then these disturbances may negate any benefits of conservation tillage.

Stubble retention has been widely recommended to farmers in southern Australia. However, the case for stubble retention in central and southern NSW has been more difficult to justify, as the key drivers of benefit and adoption of the practice are less clear. Erosion from intense summer rains, as in Queensland, is rarer and the soils are not as prone to wind erosion as some soils in WA. Further, as presented in the current monograph, the effects on grain yield of stubble retention are largely negative, using current technology. The farmer has additional costs, (machinery modification or purchase, and potentially increased field operations to roll/slash/harrow stubble, and potentially increased application of pesticides and nutrients) and may not receive an economic benefit. Other benefits of the change in stubble-retention practice are possibly accruing to the community, through reduced smoke pollution and reduced turbidity and nutrient concentrations in waterways.

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GLOSSARY OF TERMS

Where possible in this monograph the terms below have the meaning given. However, the terms used in the papers reviewed have been accepted if a lack of detailed descriptions of methodology, or ambiguity in description, did not permit any reassessment.

Definitions of tillage systems:

– Multiple tillage	Two or more tillage operations before sowing.
– Reduced tillage	One pass prior to sowing.

Definitions of sowing systems:

– Direct drilling	One pass sowing with a full–cut soil disturbance.
– No–tillage[a]	Knife or disc sowing with 5–20% disturbance with no prior tillage.
– Zero–tillage[a]	Disc sowing with <5% soil disturbance, with no prior tillage

[a] In some regions and usage the terms “no-tillage” and “zero-tillage” can imply that stubble is retained intact prior to sowing. In other situations the stubble may be burnt or removed.

Definitions and descriptions of stubble:

– Stubble	Plant residue left in the field after harvest, including stem, leaf and glume of cereals.
– Straw	Stems only of cereals
– Standing	Upright stems, with only the disturbance of harvesting machinery.
– Mulched	Stubble lying as a layer on the soil surface. This can be achieved by using a flail mulcher, slasher, harrow or roller. This can also mean cultivation with a blade plough with wide sweeps intended to cultivate and leave a maximum amount of stubble on the soil surface.
– Incorporated	Mixing the stubble into the cultivation depth; usually with a disc plough, disc harrow or scarifier.
– Retained stubble	Stubble remaining in the field without removal or burning. Stubble may be incorporated, mulched, slashed etc or left standing.

1. INTRODUCTION

Stubble retention in cereal farming systems in southern Australia has been the subject of research for 30 years (Fawcett, 1978; Marston and Hird, 1978) . The potential benefits of stubble-retained systems are primarily related to minimising soil erosion risk and within season benefits on soil moisture, as well as other soil benefits which may accrue over years. The practical problems with stubble retention are related to difficulties with crop establishment using conventional machinery, disease carry over on stubble, weed control and immobilisation of nitrogen. These component benefits and problems vary with growing season, soil type, crop and region, but are generally negative in relation to yield of grain, when compared with systems of stubble burning or stubble removal (Kirkegaard, 1995). The suggestion that stubble burning may be banned through legislation gives impetus to the current monograph.

To isolate the impacts of stubble retention it is necessary to distinguish between stubble removal (usually by burning) and cultivation (tillage). That is, it is necessary to “decouple” the components of “conservation farming” into changes in cultivation practice and changes in stubble management. The promotion of “conservation farming” including both reduced and non tillage, with or without stubble retention can be misleading. Thus the retention of stubble often requires reduced cultivation, although blade ploughs and rod weeders can cultivate while retaining crop stubble on the soil surface. The reverse does not hold, as stubble burning or removal does not necessitate any tillage. The progress to total conservation farming (zero-till with stubble retention) appeared to be evolutionary in the sense that there has been widespread adoption of minimum tillage and slower adoption of stubble retention. For example, in north-eastern Victoria, direct drilling (100% soil surface disturbance in one pass sowing) has gained acceptance by farmers and stubble retention, rather than burning, is seen as a “next step” in the adoption of conservation farming practices (Steed et al., 1994). Similar findings have been encountered in southern and central New South Wales (NSW).

The purpose of the current monograph was to assemble quantitative data relevant to yield benefits and soil improvements associated with the adoption of stubble retention. Equally, data were sought on any penalties to the farming system as a result of stubble retention. Current evidence outlining advantages and disadvantages of stubble retention was reviewed, usually in a direct drill, no-tillage (5-20 % of soil surface disturbed by sowing) or zero-tillage (< 5 % soil surface disturbance) setting. Central and southern NSW were the primary regions of interest and some unpublished data from these areas are presented, with further data from southern Australia believed to be regionally relevant. Reasons for adoption of stubble retention and the perceived reasons for low adoption in some regions are examined and areas of possible future research are identified.

1.1 Stubble Management by Farmers

The most frequently burnt stubbles in Western Australia (WA) in 2005 were wheat (Figure 1, Smith et al., 2007). A similar pattern seems likely in central and southern NSW, Victoria and South Australia (SA), although no data are available.

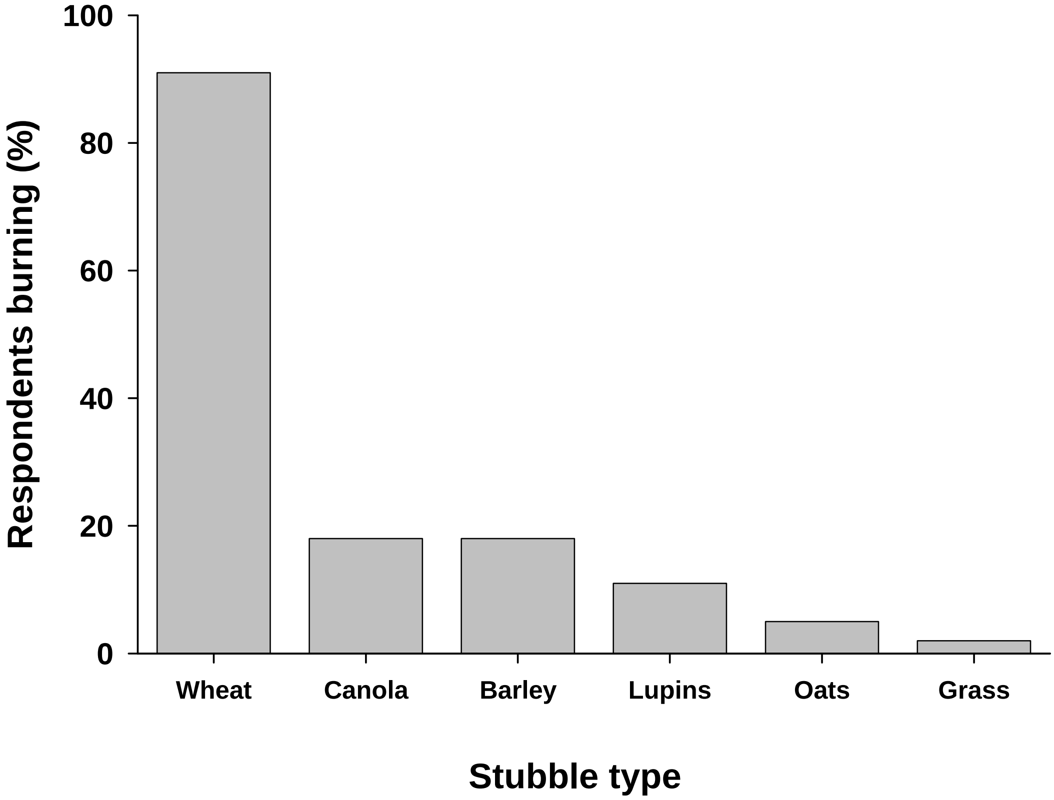

Figure 1. Types of stubble burnt by farmers in south-western Australia in 2005, based on a postal survey with 273 responses. Source: Smith, et al. (2007), reprinted with permission[1].

The move from stubble burning as the major method of stubble management in the cropping areas of Australia has been uneven. In Queensland burning of stubbles has been almost abandoned, with only 4% of crop residues burnt in 2001 (Figure 2A). Burning has been replaced by incorporation of stubble by ploughing (38%) and the practice of sowing into intact stubble (30% adoption). When sowing into intact stubble, the crop was sown using zero-tillage (5-20% disturbance of the soil surface with knife points or disc seeders), no-tillage (< 20% soil disturbance with narrow points on tynes) or direct drilling (full cut soil disturbance using wider points on tynes). Herbicides were used to control weeds in the crop stubble over summer.

In WA approximately 17% of stubbles were burnt in 2001 and most crops were sown by no-tillage/direct drilling into previously undisturbed stubble (54%). Typical rotations in WA included wheat/annual medic/wheat and in this system wheaten stubble would not be burnt, because in the year following wheat the pasture regeneration would be damaged. For the common wheat/lupin system of WA usually only stubbles of wheat would be burnt, with lupin or canola stubbles seldom burnt (Figure 1).

In NSW, Victoria and SA burning was more common (24–35% of stubbles burnt), particularly in NSW and Victoria. In these states the next most common practices were to incorporate the stubble by ploughing (32% in both regions), or to sow with no prior cultivation (18 and 13%).

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Within NSW, stubble management practice has been disaggregated into northern, central and southern (Figure 2B). The data have been confined to the cereal cropping areas only and excluded some smaller cropped areas (i.e. vegetable and sugar cane crops on the north coast of NSW). The aggregate values for NSW were within 1% of the frequency values reported in all states (Figure 2A). Stubble burning was less frequent in northern NSW (11%), compared with central and southern areas of NSW (34 and 51%, respectively). Northern NSW reflects practices in common with those in Queensland (4% burnt). Ploughing in of stubbles was also more common in northern NSW (41%) than in the south of the state (14%).

Satellite technology has recently been used to detect fire hot spots from stubble burning (Figure 3). The time represented in Figure 3 (12 weeks from the 1st of March in 2005) would include most stubble burning events. Autumn burning of stubble has become the common practice in southern Australia; burning immediately after harvest (December, January) was the most common practice in northern NSW (Martin et al., 1988) and Queensland.

While not all fires were detected, due to cloud cover on some satellite passes, some general conclusions can be draw. Greatest fire frequency was identified in southern NSW in the higher rainfall eastern areas, with less frequent burning of stubbles in the more western areas where rainfall tends to be lower. Other areas of intensive burning appeared in north-eastern Victoria, the high rainfall areas of Victoria near Hamilton, in SA on the Yorke Peninsula and areas to its north, and the eastern part of the northern wheat belt of WA. The intensity of burning in the northern wheat belt of WA in the 2005 season was unexpected as burning was not a common practice in WA in 2001 (Figure 2A).

Frequent burning of stubble in central and southern NSW was confirmed during 2008 by a phone survey of 1172 growers from Australian cropping areas (Llewellyn and D'Emden, 2009). An estimated 33% and 47% of growers burnt some stubble in central and southern NSW respectively, while the median area burnt was 40% and 50% of stubble area respectively (Table 1, Llewellyn and D'Emden, 2009). Therefore, the total area of stubble burnt in central and southern NSW respectively was approximately 40% and 50% of stubble area for 33% and 47% of growers, or approximately 13.2% and 23.5% of entire stubble area for those regions. Growers in the western central region of WA and the Loddon region of Victoria also burnt significant areas of stubble (approximately 10% and 7% of entire stubble area respectively), while growers in southern Queensland burned less than 1% of entire stubble area. Burning was particularly widespread in the western central region of WA, with 55% of responding growers burning some stubble.

Table 1. Percentage of respondents who burnt some stubble, median area of stubble burned in each area and proportion of respondents burning greater than 10% of stubbles from a phone survey of 1172 growers conducted in 2008.

State[1]	Region[2]	Growers burning some cereal stubble (%)	Median area of cereal stubble burned (%)	Proportion of all respondents burning ≥ 10%
NSW	***All***	***25***	***42***	***23***
	Central West	33	40	30
	Mallee	0	-	-
	Northern	10	30	8
	Southern	47	50	46
Qld	Southern	7	9	3
SA	***All***	***7***	***10***	***9***
	Central West	23	10	17
	Lower EP	38	10	20
	Mallee	9	10	8
	Upper EP	2	-	-
	Western EP	3	-	-
Vic	***All***	***23***	***20***	***19***
	Loddon	30	23	27
	Mallee	9	10	6
	Wimmera	33	15	24
WA	***All***	***33***	***10***	***23***
	Central/Eastern	33	10	25
	Midlands	35	6	15
	Northern	24	10	12
	SE Central	23	10	16
	Upper Great Southern	32	10	22
	Western Central	55	18	45
All respondents		22	20	12

[1] Qld = Queensland, SA = South Australia, Vic = Victoria, WA = Western Australia.
[2] EP = Eyre Peninsular.
Source: Llewellyn and D'Emden (2009), reprinted with permission[2].

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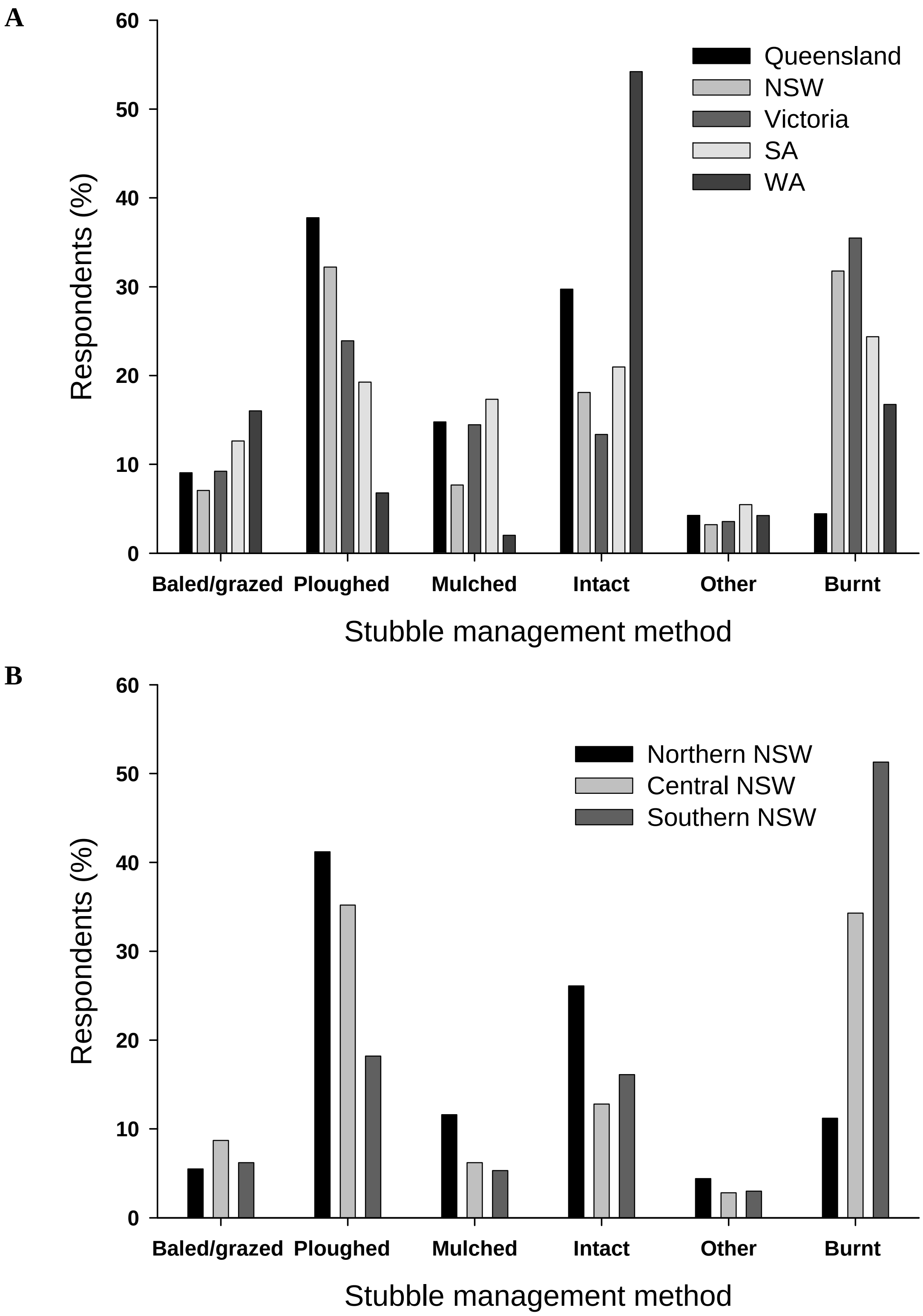

Figure 2. Methods of stubble management (A) by state, and (B) within New South Wales. Figure A adapted from Australian Bureau of Statistics, 2001 Agricultural Census. Figure B adapted by F. Scott, pers. comm.

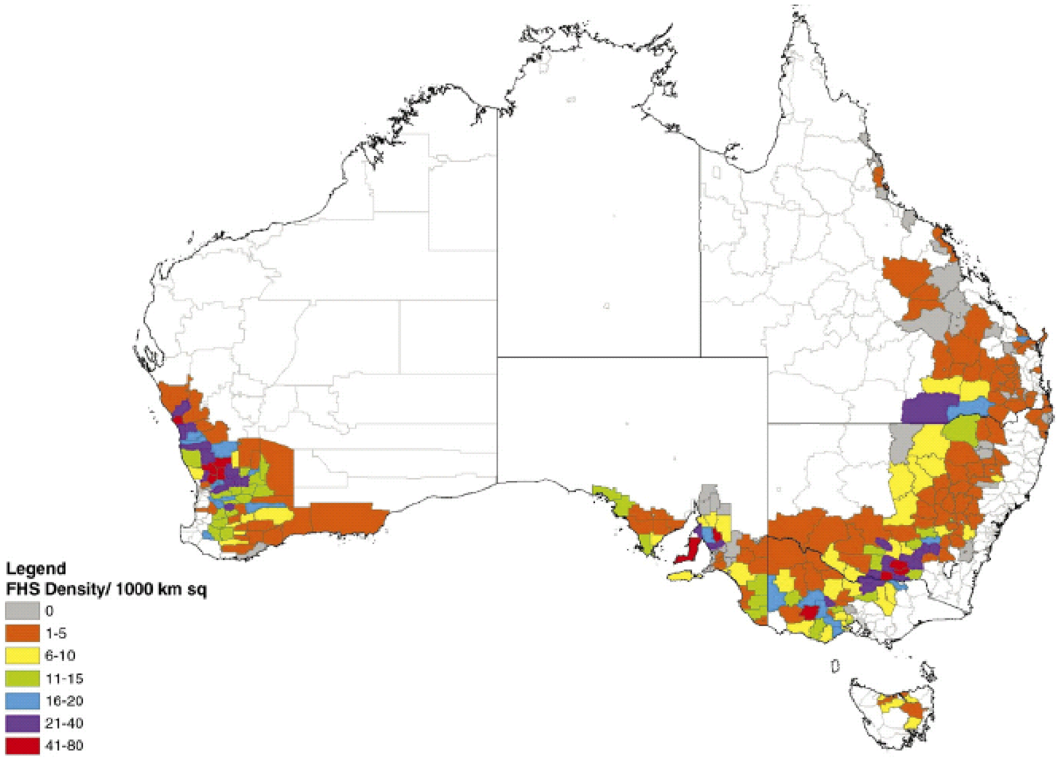

Figure 3. Fire hot spot density (FHS/1000 km^2) in the 12 weeks from 1st March 2005 in Local Government Areas of Australia with significant cropping. Source: Smith et al. (2007), reprinted with permission[3].

Stubble management in southern NSW was investigated in a postal survey of 700 dryland farmers (Davis, 2006). The most common practices (Figure 4A) were to graze stubbles (69%), burn stubble (49%), control weeds in the stubble by spraying (39%) and to cultivate the stubble (28%). The percentage responses (Figure 4A) add to greater than 100%, indicating that farmers used multiple stubble management practices. Stubble grazing, spraying and burning were used in combination by 14.4% of respondents, while grazing alone was used by 14.1%. The grazing and spraying of stubble may have been intended for weed control in the retained stubble during summer and early autumn. The 9% of respondents reporting stubble retention and no spraying may have been in situations where grazing or a dry season made weed control by spraying unnecessary. Of all respondents, 57% reported using no cultivation or cultivated only under special circumstances. Cultivation, when it was used (39% of respondents), was not intensive, as 23% of respondents reported cultivating only once prior to sowing. Reduced tillage may be intended to reduce stubble load by incorporation, assist in preparing a seed bed, control weeds, or for soil conservation (McNeill and Aveyard, 1978). Only 16% of respondents used multiple cultivations prior to sowing. When stubble was burnt, this occurred mainly in autumn (March to May, Figure 4B) and, on 70% of occasions, this was 1 to 4 weeks prior to sowing.

When farmers were asked the reasons they used stubble reduction practices (such as burning), the dominant reasons given were that the unmanaged stubble would be too thick to sow through (69% of respondents), would promote disease (34%), would hinder weed management (32%), or that they wished to use soil incorporated pre-emergent herbicide (30%). Stubble retention presented a barrier to the herbicide contacting the soil and being

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successfully incorporated. Asked to nominate, from a list, their reasons for retaining stubble they nominated conserving soil moisture (75%), increasing soil organic matter (69%), improving soil structure (61%) and maintaining ground cover to prevent erosion (56%).

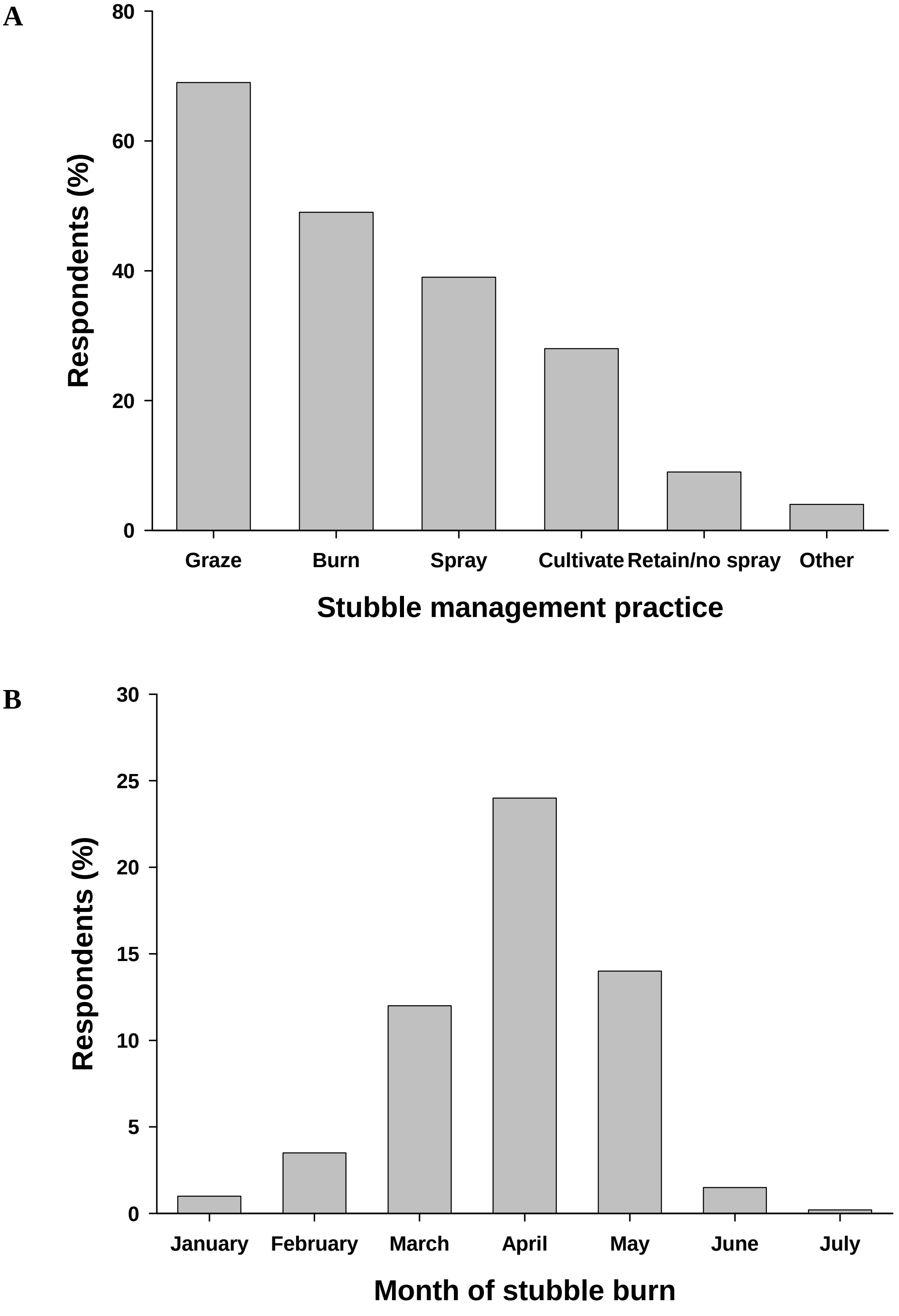

Figure 4. The percentage of respondents in a postal survey of 700 dryland farmers in southern NSW for (A) their stubble management practices and (B) the time of burning of stubbles. Source: Davis (2006).

In many southern areas more frequent stubble burning was most likely associated with areas producing heavier stubble, which presented problems with sowing of a subsequent crop. In WA there seemed to be some inconsistency on frequency of stubble burning. Australian Bureau of Statistics data for the 2001 census indicated only 17% of stubbles were burnt in WA. However, more frequent stubble burning in WA was reported in the northern wheat belt in 2005 (Smith et al., 2007) and in many other areas, particularly the western central wheat belt, in 2008 (Llewellyn and D'Emden, 2009). In WA stubble burning appeared to be used opportunistically to reduce heavy stubble loads after favourable seasons.

Many farmers have "decoupled" the components of conservation farming (tillage reduction and stubble retention), and adopted them independently of one another. In the northern wheat belt of eastern Australia (Queensland and northern NSW) stubble retention has been adopted, but tillage has frequently been maintained. Common practices were ploughing to incorporate stubble, and stubble mulching with blade ploughs and rod weeders used but stubble was retained on the soil surface. By contrast in the south east of Australia although farmers recognise the potential advantages from stubble retention, and tillage has been reduced (no tillage prior to sowing or one cultivation only), stubbles were more commonly burnt. In southern NSW the issue for farmers was the difficulty of sowing the following crop through heavy stubble. In the northern wheat belt the combined effects of higher summer rainfall, cultivation and partial burial of stubble may hasten stubble breakdown between crops and reduce this difficulty.

1.2 Potential Advantages and Disadvantages of Stubble-retained Systems

The advantages and disadvantages of stubble retention can be divided into short-term and long-term effects (Table 2). Short-term advantages of stubble retention are mainly due to the presence of the current stubble, which provides protection of the soil surface from wind and rain, mitigating erosion of the soil surface. Long-term advantages are due to improvements in conditions for plant growth, which may contribute to either maintaining or sequestering soil organic carbon (SOC) which would otherwise be lost by burning or stubble removal.

Improved water infiltration may result from the short-term presence of stubble and, in the longer term, from improved soil structure. In part this infiltration is related to greater macro-porosity resulting from increased earthworm populations. Stubble also increases soil moisture retention, particularly in the surface soil pre-sowing and in early crop development (Poole, 1987).

Farmers perceived that the short-term disadvantages of stubble retention were dominated by the interference with sowing operations. The major disadvantage perceived in conservation farming systems in the long term was an increased reliance on herbicide use that could lead to the development of herbicide resistance in weeds.

Table 2. Potential advantages and disadvantages of stubble retention**.**

Advantages	**Disadvantages**
Short-term	Short-term
1. Reduced wind and water erosion	1. Interference with machinery
2. Improved water infiltration, reduced evaporation and increased soil water storage	2. Loss of complementarity with livestock enterprises in mixed farming
3. Reduced spread of some diseases	3. Disease carry over on stubble retention vs burning
4. Conservation of nutrients	4. Pest carry over on stubble
5. Avoidance of the smoke hazard from burning	5. Effect of stubble retention vs burning on weed populations
	6. Stubble impact on herbicide spraying and incorporation
	7. Immobilisation of N by retained stubble
	8. Allelopathic effects of retained stubble
	9. Physical effects of retained stubble (temperature, light)
Long-term	Long-term
6. Effects on soil organic carbon (SOC)	10. Development of herbicide resistance in weeds
7. Increased earthworm numbers	11. Stratification of the soil profile

Adapted from Poole (1987).

The potential advantages and disadvantages of stubble were influenced by several factors. For example stubble type can vary between cereal species and between cereals and pastures, canola and pulse crops; the amount of stubble retained varied with seasonal conditions for crop growth and management of the stubble, which can be left standing, flattened, slashed, mulched with a blade plough or incorporated: and decomposition or grazing of stubble can change the quantity and nature of stubble from time of harvest to sowing. The aim in producing a universally acceptable method of stubble management may be to manage the amount and architecture of stubble to maximise benefits, but minimise disadvantages.

Quantification of stubble loads has generally been inadequate and inconsistent, with the most common measures being the proportion of ground cover and weight of stubble present. Ground cover was most frequently quoted in studies on soil erosion, and weight was reported in agronomic studies, particularly studies dealing with machinery, cultivation, or sowing. However, other than larger amounts of stubble being associated with more ground cover, there appeared to be a variable relationship between these two measurements (Figure 5). To achieve a ground cover target of 60%, for example, could require an amount of wheaten stubble varying between 0.8 t/ha to greater than 3 t/ha.

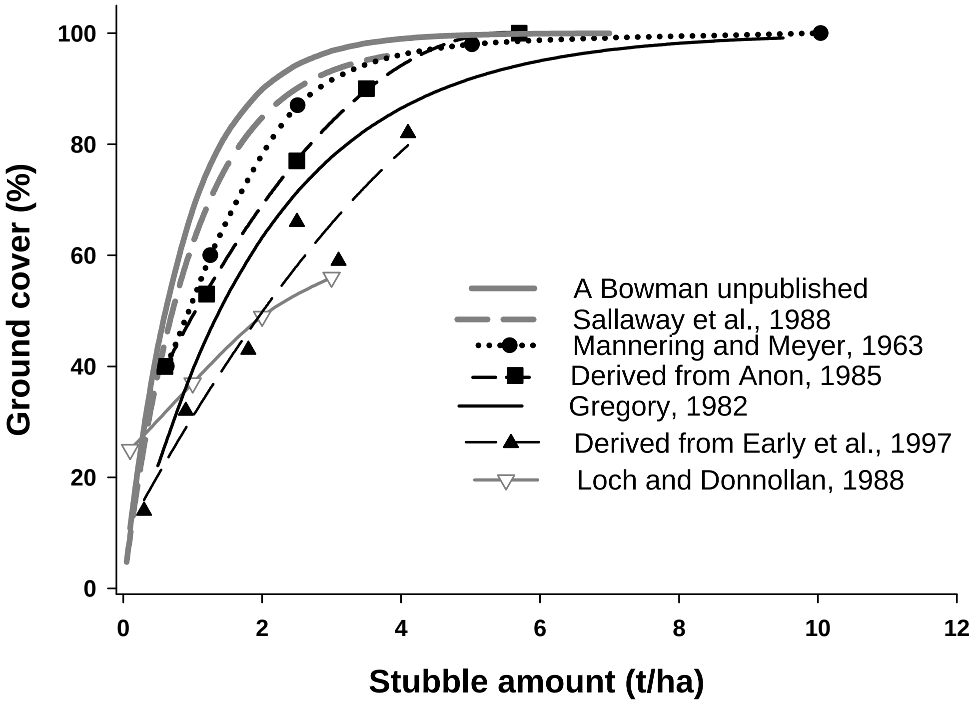

Figure 5. The relationship between stubble amount (t/ha) and projected ground cover (%) for stubble of wheat from A. Bowman, unpublished, Sallaway et al (1988), Mannering and Meyer (1963), Anon (1985), Gregory (1982), Early et al. (1997) and Loch and Donnollan (1988).

The most comprehensive study relating the amount of stubble with percentage ground cover was conducted in Queensland (Figure 5, Sallaway et al., 1988). Wheaten stubble amounts and ground cover were recorded after harvest, in three seasons. A series of cultivations followed and ground cover and stubble amount were recorded. Data from Bowman described the amount of ground cover from five cereal stubbles monitored over summer in southern NSW, while they were intermittently grazed, however, these data have not been published.

Other studies appear to be somewhat “contrived”. These studies involved the use of straw (stems) only rather than the stubble (stems, leaves and glumes) which occurs in the field. In the study of Mannering and Meyer (1963) in the USA, wheaten straw was placed on to previously cultivated plots and ground cover measured. Ground cover was also estimated from the area covered by known weights of straw (Gregory, 1982), where final estimates were made either directly in the field on stubbles or by placing baled straw on the soil surface. Photographs of prostrate stubble have been presented as photo standards for farmer use and stubble weights were given (Anon, 1985; Early et al., 1997). Ground cover was derived from the photographs and the relationship between stubble weight and ground cover was determined. In handling stubble it is likely that leaf and glume were lost, so that the tendency was to underestimate ground cover (Anon, 1985; Early et al., 1997; Gregory, 1982). Loch and Donnollan (1988) prepared their plots by pulling wheat plants from a 6 t/ha stubble to achieve lower amounts (1, 2 and 3 t/ha) and by burning the stubble, which left 0.1 t/ha of stubble. The plots were cultivated with a blade plough so stubble was dominantly prostrate and tended to be accumulated in distinct bands. The resulting relationship between stubble cover and amount of stubble appeared different from the other studies reported (Figure 5).

Data from field experiments were the most relevant to Australian conditions (Bowman, unpublished, Sallaway et al., 1988). From these it was concluded that higher ground cover of stubble may have been produced by standing stubble, with leaf and glume present. These amounts will be reduced after several cultivations with either a blade or disc plough or scarifying (Sallaway et al., 1988), or after grazing and trampling by stock (Bowman unpublished).

2. BENEFITS OF STUBBLE RETENTION

2.1 Reduced Wind and Water Erosion

2.1.1 Wind erosion

Crop stubble can protect the soil surface from wind erosion by slowing wind speed within and above the stubble. Wind speed at the ground surface was estimated to be 0.15 to 0.20 of the wind speed at 2.4 m above the ground in two standing stubbles of wheat (Figure 6, Aiken et al., 2003). Stubble height or horizontal profile was seldom reported in the Australian literature, although either may influence wind speed and microclimate at the soil surface; standing wheaten stubble was particularly effective in slowing wind and minimising erosion. On a weight basis, wheat was 5.5 and 8.7 times more effective than standing sorghum or maize stubble (Lyles and Allison, 1976). Using wind tunnel studies, standing wheaten stubble was 1.4 to 2 times more effective where rows were across the wind direction, rather than parallel to the wind (Lyles and Allison, 1976).

In WA wind erosion on coastal sandy soils has been an issue, particularly where lupins (*Lupinus angustifolius* L.) were sown (Findlater et al., 1990). Stubbles of lupin drop leaf and were commonly grazed over summer. Stock trampling resulted in a more prostrate rather than upright stubble, sometimes weakening the point of anchorage of the stubble to the soil.

Findlater et al. (1990) used a wind tunnel and modelling approach to study the protection offered to sandy soils prone to erosion by prostrate lupin stubbles. The stubbles ranged from 1-10 t/ha with from 20-95% ground cover and bare soil was included as a control. Approximately 50% ground cover appeared to be required to minimise erosion soil loss (Figure 7). Subsequently, a ground cover of 50% with prostrate stubbles and 20-30% cover with standing stubbles was recommended to minimise wind erosion risk (Findlater and Riethmuller, 2000). If prostrate residues were easily detached (i.e. pea stubbles) then much higher amounts of stubble were required to protect the soil surface.

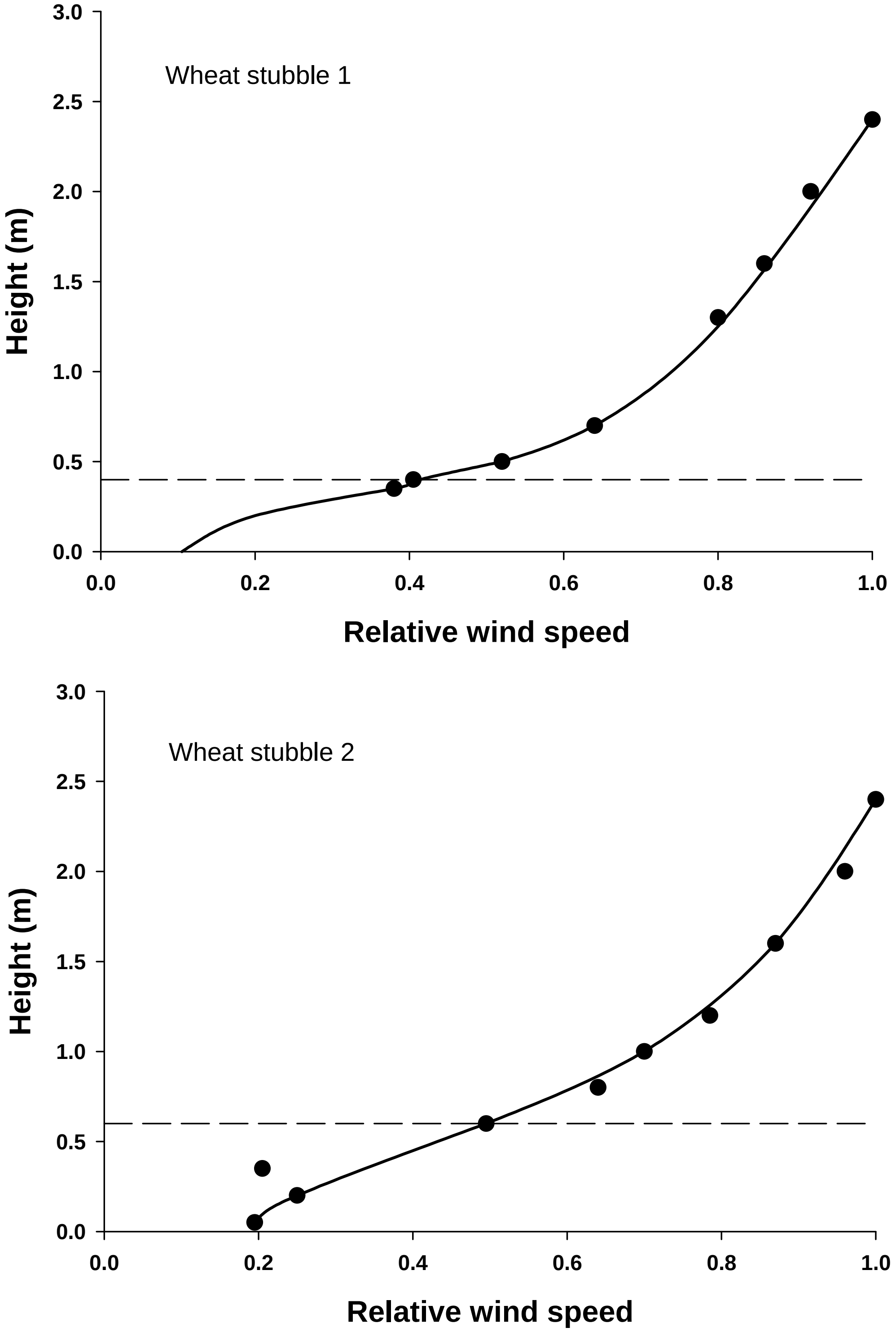

Figure 6. Wind speed in and above two wheaten (wheat) stubbles relative to the wind speed at 2.4 m above ground level. The data were fitted to a mechanistic model. Stubble 1 was 0.40 m in height (broken line) with 453 stems/m^2, while stubble 2 was 0.6 m in height with 156 stems/m^2. Both crops were sown with 30 cm row spacing. Source: Aiken et al. (2003), reprinted with permission[4].

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[4] ©American Society of Agronomy (2003), 16 Nov 2009

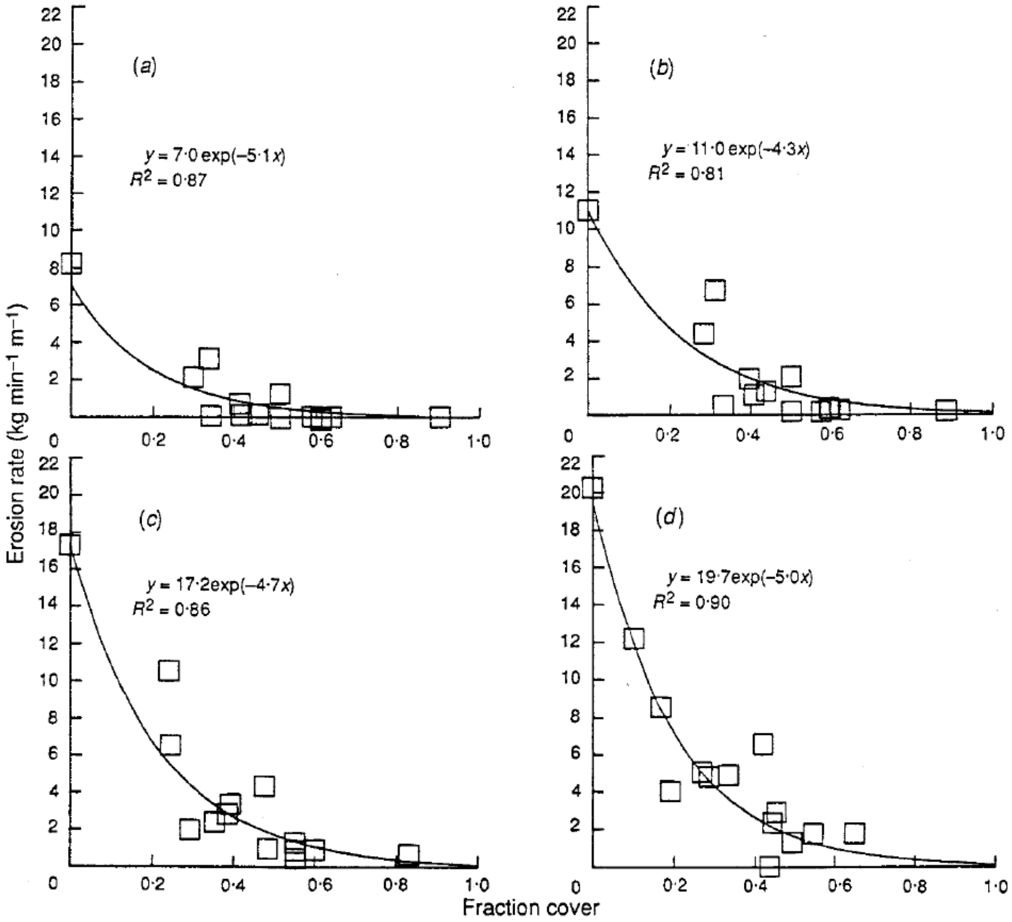

Figure 7. The influence of ground cover from prostrate lupin stubble on erosion rate from sandy soil with varying winds speeds (recorded 65 cm above ground) of (a) 13.4 m/s, (b) 15.4 m/s, (c) 16.9 m/s and (d) 18.6 m/s in a wind tunnel experiment conducted in the field. Source: Findlater et al. (1990), reprinted with permission[5].

2.1.2 Water erosion

The impact of raindrops can dislodge soil particles and make them more prone to being eroded in the event of water runoff. Retention of stubble offers an opportunity to protect the soil surface from direct effects of rain drop impact and reduce soil surface runoff and any associated soil loss.

Erosivity of annual rainfall in Australian cereal cropping areas was greatest in the cropping areas of Queensland and northern NSW and lowest in the southern mediterranean climates of WA, SA and western Victoria (Figure 8). The wheat belt of central and southern NSW and parts of Victoria, were intermediate in rainfall erosivity.

Greater erosivity is associated with high intensity summer rainfall, for example, similar to that occurring at Dalby and Clifton in Queensland (Freebairn and Wockner, 1983). The risk of erosivity in winter is minimal as rainfall is low (Figure 9). In south-eastern regions, for example at Wagga Wagga in NSW, rainfall was only slightly winter dominant, but erosivity risk was highest in summer because of high intensity rainfall events (Figure 9, Yu and

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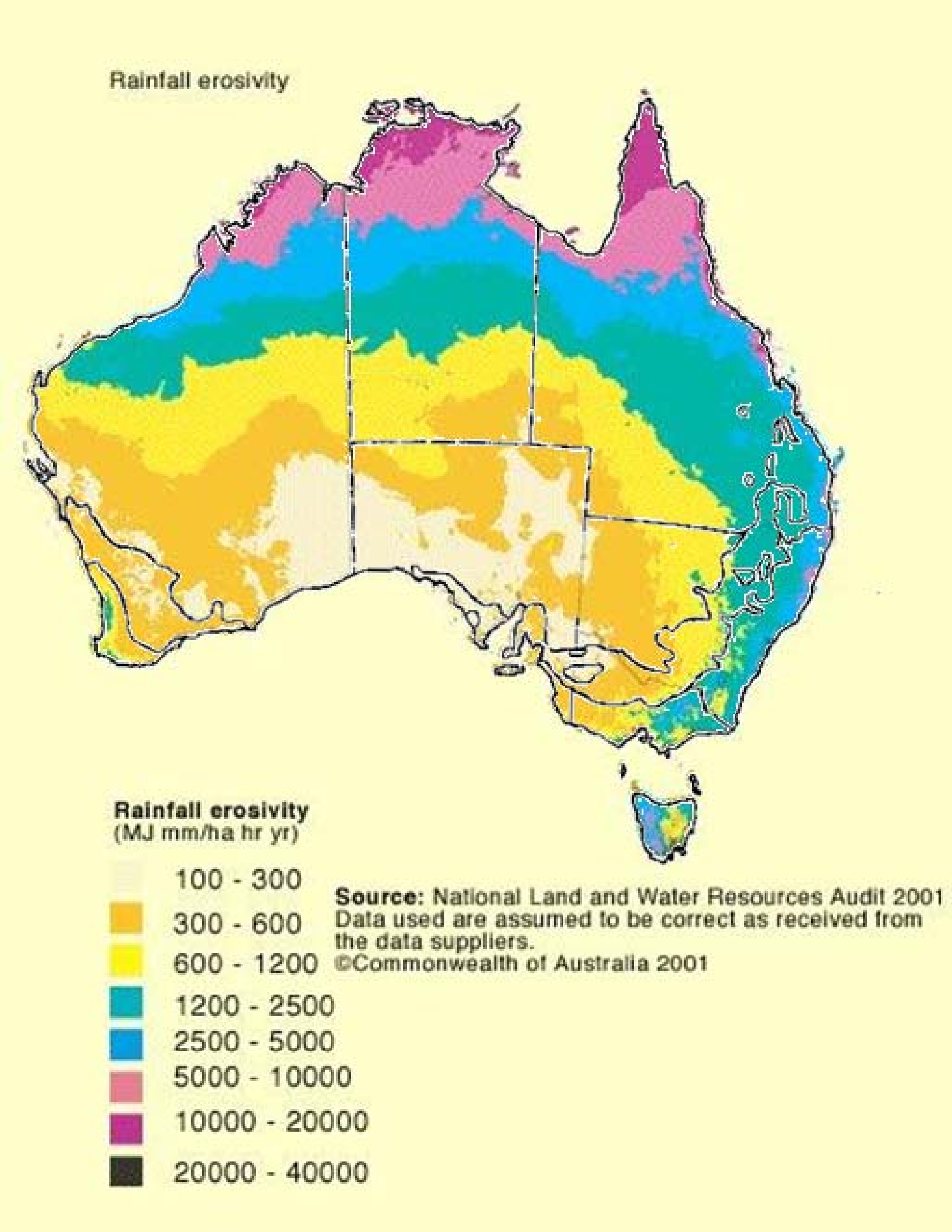
[5] ©CSIRO Publishing, Collingwood Vic (1990), 2 Oct 2009

Rosewell, 1996). However, with the practice of later burning of stubble, the summer risk can be managed by the presence of stubble. The critical period would be after stubble burning in March/April when the soil surface was exposed and there remained a "window" of risk before crops emerged and established some ground protection, usually by winter (June/July). At Wagga Wagga, stubble retention in autumn, compared with stubble burning, has resulted in reduced runoff from direct drilled wheat (15 compared with 25 mm/year) and decreased soil loss (0.5 compared with 1.4 t/ha.year) as measured over 40 months on a site of 8% slope (Barker, 1989).



Source: National Land and Water Resources Audit 2001
Data used are assumed to be correct as received from the data suppliers.
©Commonwealth of Australia 2001

Figure 8. Erosivity of annual rainfall in Australia (Source: Anon, 2001), reproduced with permission[6] with an overlay of wheat cropping areas of Australia added from Cramb (2000).

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[6] ©Commonwealth of Australia (2001), 3 Sept 2009

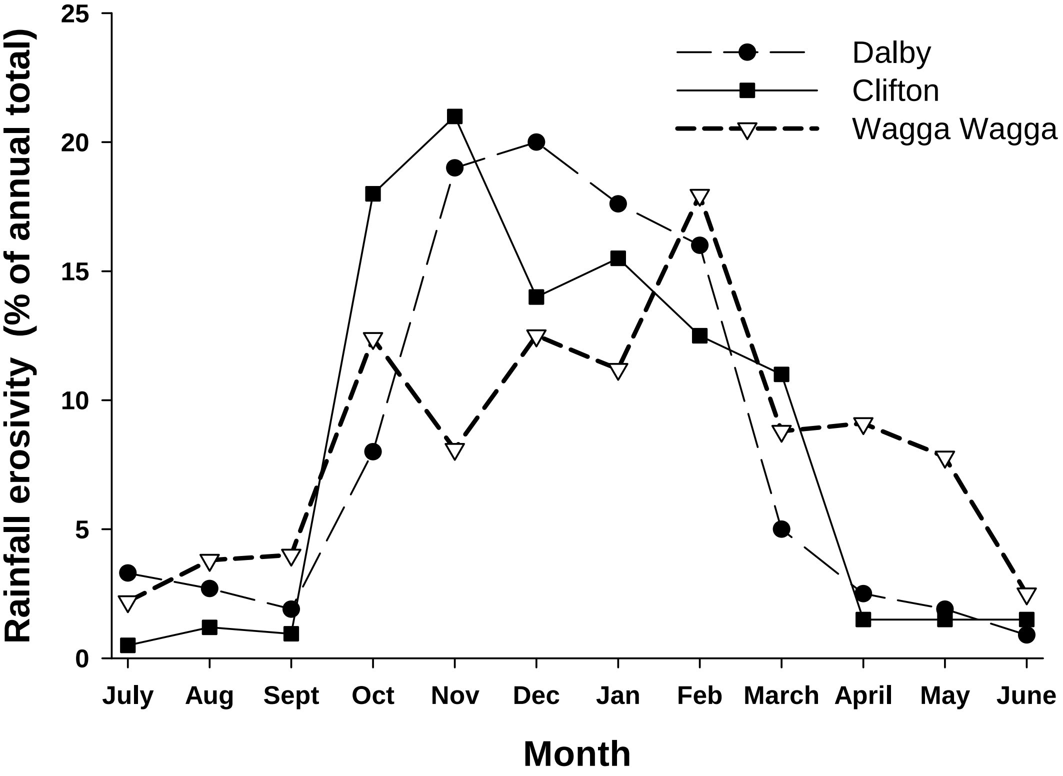

Figure 9. Monthly distribution of rainfall erosivity at Clifton and Dalby in Queensland and Wagga Wagga in southern New South Wales. Source of data for Queensland: Freebairn and Wockner, (1983), reproduced with permission[7], with an additional plot added for Wagga Wagga: Yu and Rosewell (1996).

Studies on small catchments in Queensland demonstrated that the presence of stubble on the soil surface reduced runoff and soil loss (Table 3, Radford et al., 1993). This benefit may have driven the adoption of conservation tillage practices in Queensland (Freebairn and Silburn, 2004; Freebairn and Wockner, 1983).

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Table 3. Effect of fallow management practices on annual soil movement (t/ha) and runoff (mm) at four sites in Queensland under a range of stubble types with the addition of site slope.

Fallow management practices	Soil movement (t/ha) and Runoff (mm)[5]					
	Greenwood[1] (Slope 6.7%)	Greenmount[2] (Slope 4-5%)	Capella[3] (Slope 1.6-2.5%)			Brigalow[4] (Slope level)
	Wheat 1978–82	Wheat 1979–89	Wheat 1984–87	Sorghum 1983–87	Sunflower 1983–87	Wheat 1986–90
No-tillage	1 (31)[5]	3 (61)	0.7 (6)	1.5 (54)	4.4 (46)	0.0 (62)
Stubble mulch	3 (27)	6 (53)	0.3 (8)	4.0 (59)	6.0 (66)	0.5 (56)
Stubble incorporation	7 (35)	16 (56)	1.8 (24)	8.0 (59)	7.4 (70)	nd (nd)
Stubble burnt	31 (55)	49 (74)	nd (nd)[6]	nd (nd)	nd (nd)	nd (nd)

Source: Radford et al. (1993), reproduced with permission[8] and cited by Thomas et al. (2007).
[1]Freebairn and Wockner (1983), grey clay.
[2]Wockner and Freebairn (1991), black earth.
[3]Carroll et al. (1988), black earth.
[4]Thomas et al. (1990), grey clay.
[5]Runoff (mm) in parenthesis.
[6]nd = not determined.

2.2 Improved Water Balance and Increased Soil Water Storage

2.2.1 Water infiltration

Stubble burning may directly affect some soil properties. At Cowra in central NSW, a comparison was made of water infiltration rates, using a disc permeameter, in paired areas, each of 1 m^2, in which the stubble (2.8 t/ha) was burnt in one treatment and retained in another (Valzano et al., 1997). Stubble and ash were removed from the burnt plots prior to measurement.

Although burning had no significant effect on volumetric moisture content or bulk density in the 0-40 mm layer, sorptivity, final infiltration rate and hydraulic conductivity were decreased by approximately 50% in the burnt plots. Clay dispersion and aggregate stability were unaffected by the low intensity burn and no water repellency was recorded before or after the low intensity fire. While the mechanisms causing these effects on hydraulic properties were as yet uncertain, the authors suggested blockage of macro-pores by fine ash particles. This experiment highlighted the need to separate the short- and long-term effects of stubble burning and stubble retention on water infiltration.

Stubble mulch effectively increases water infiltration by reducing surface water run off. Infiltration rates of simulated rainfall were greater when increasing amounts of stubble (most likely straw only) was applied to the soil surface in Northfield SA (Figure 10A, Malinda et al., 1994). This experiment demonstrated only the short-term effects of straw, as the plots were selected in the field and straw added on one occasion. Similar long-term effects were also demonstrated in Tarlee, SA in 1988-1990 on plots established in 1984 (Figure 10B, Malinda, 1995).

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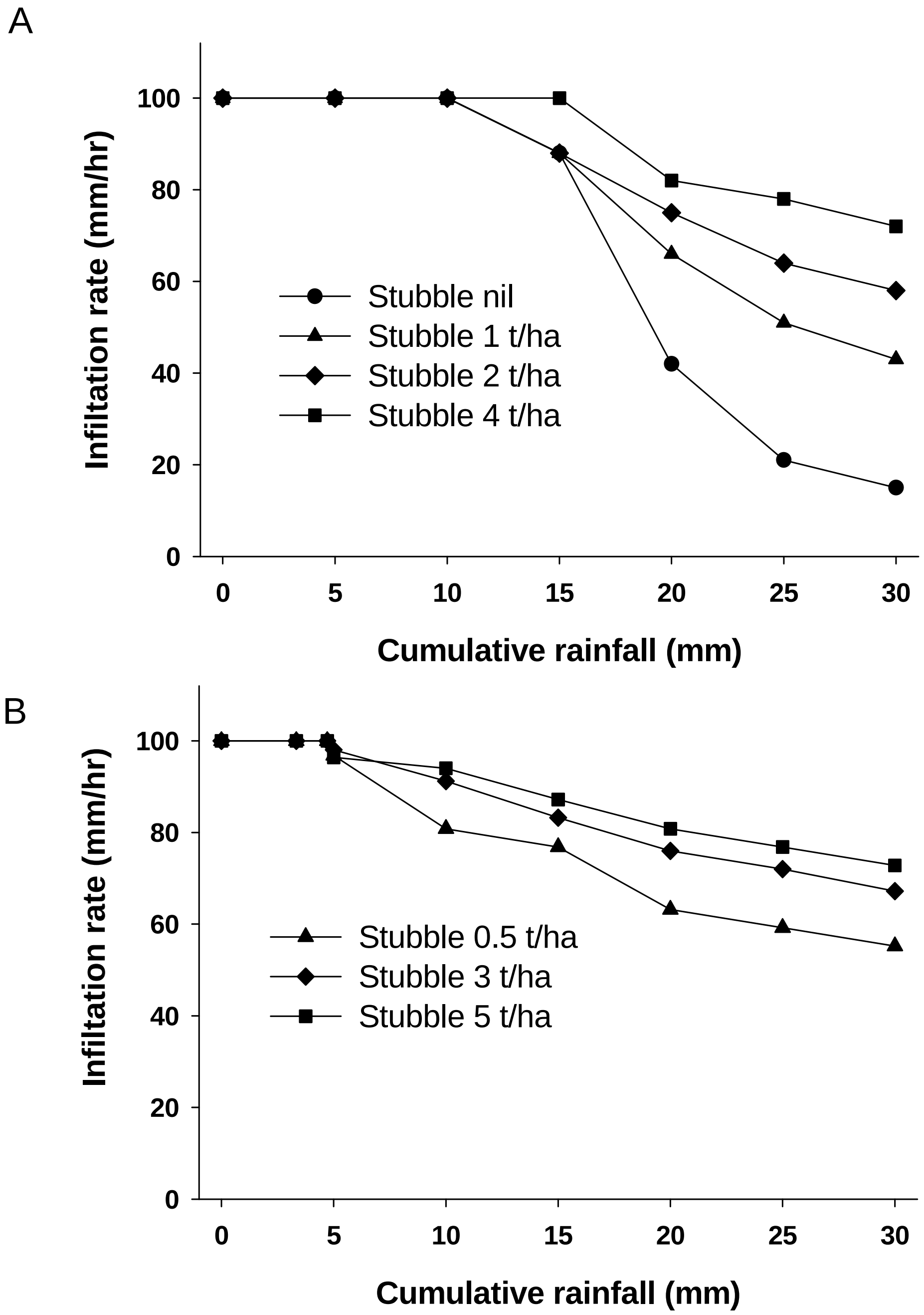

Figure 10. Effect of stubble on infiltration rate in rainfall simulation studies at (A) Northfield SA with no-tillage and added straw and (B) Tarlee SA where data have been averaged over tillage treatments, surface conditions and simulation times. Sources: Figure (A): Malinda et al. (1994), reprinted with permission[9], Figure (B): Adapted from: Malinda (1995).

In long-term experiments, improved infiltration with stubble retention has been ascribed to a slow improvement over time in soil structure or structural stability, and improved macro-porosity due to soil fauna. There remains the likelihood that part of this advantage may be due to short-term adverse effects resulting from stubble burning, or to short-term benefits of the presence of stubble on infiltration rate.

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[9] ©Australian Society of Soil Science Inc. (1994), 16 Nov 2009

2.2.2 Stubble and evaporation of soil moisture

Prior to and, after sowing into stubble, the stubble cover may create a microclimate. This effect of stubble may reduce evaporation of moisture from the soil. Evaporative moisture loss from soil columns following a single wetting event was not different when varying amounts of wheaten straw were added up to 1.12 t/ha (Figure 11, Bond and Willis, 1969, 1970). Although soil moisture loss with first stage drying (initial constant rate drying) was lower with increasing quantity of straw, by the end of the experiment the 2.24 and 4.48 t/ha rates of straw application had lost as much soil moisture as the bare soil treatment. Greater amounts of straw (8.96 and 17.92 t/ha) slowed moisture loss even further. The effect of straw mulch was to slow soil moisture loss, and moisture loss was dependent on the amount of straw.

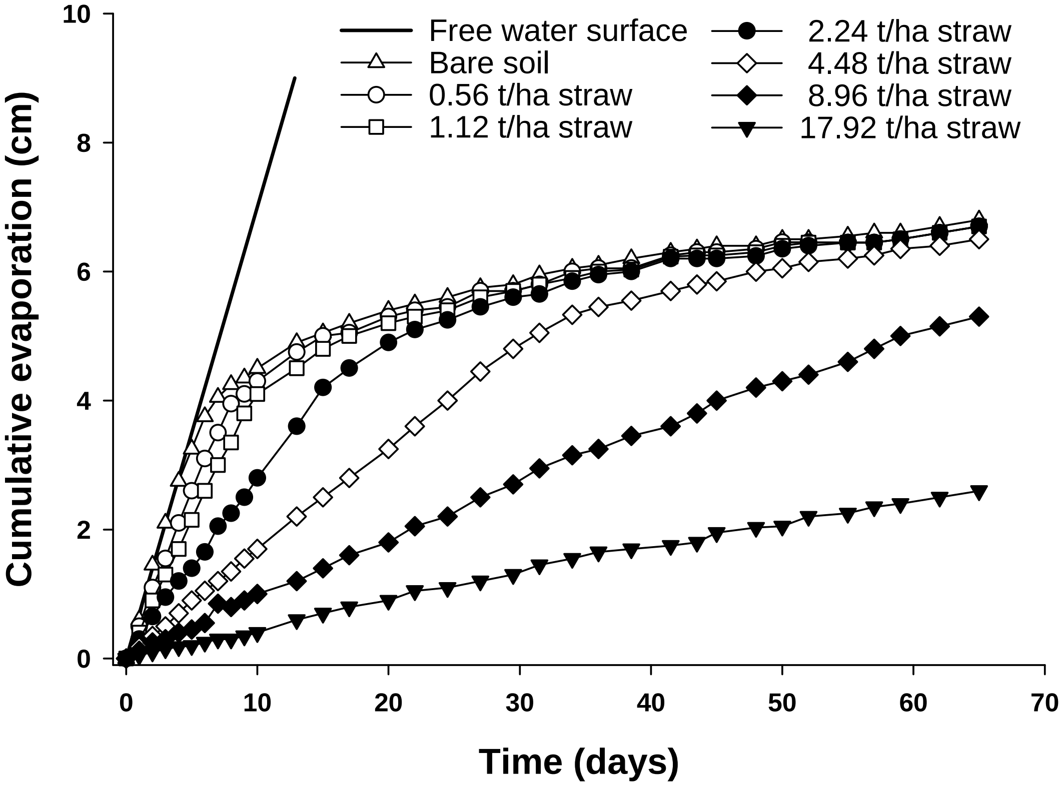

Figure 11. The effect of rate of applied wheaten straw on the cumulative evaporation from moist soil columns at an evaporative potential of 0.7 cm/day over 65 days. Source: Bond and Willis (1970), reprinted with permission[10].

Increased soil moisture storage in Akron, Colorado, was associated with an increased proportion of standing stubble (Table 4, Smika, 1983). Evaporation of soil moisture was influenced by wind speed at the soil surface and standing stubble was more effective at influencing wind speed than flattened stubble (straw cut at ground level and dispersed). The stubble was 4.6 t/ha and standing stubble was 46 cm high.

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[10] ©Soil Science Society of America (1970), 2 Sept 2009

Table 4. Water storage to a depth of 1.8 m and storage efficiency (%) for bare soil and for different straw positions on the soil surface averaged over 3 years.

	Water storage	
Straw position	Amount (mm)	Efficiency (%)[1]
Bare soil	96	18.6
100% straw flat, 0% standing	137	26.5
75% straw flat, 25% standing	234	45.3
50% straw flat, 50% standing	272	52.9

Source: Smika (1983), reprinted with permission[11].
[1] Efficiency = water stored as % of precipitation.

Soil water loss was greater with increasing wind speed regardless of the type or, position (standing or flattened), of stubble covering bare soil (Figure 12, Smika, 1983). However, standing stubble reduced soil moisture loss more than flattened stubble, which was interpreted as being due to the greater effect of standing stubble in reducing wind speed at the soil surface (Smika, 1983). The taller the standing stubble (30 to 61 cm) the lower was the wind speed at the soil surface for any given wind speed above the stubble. In addition, surface temperature was also influenced by stubble arrangement, with standing stubble giving lower temperature at the soil surface and reduced daily soil moisture loss (Table 5). Maximum temperature of the soil surface was lower and soil moisture loss reduced when mulch (3.7 t/ha of dead *Stylosanthes humata*) was present compared with when mulch was removed (Bristow, 1988).

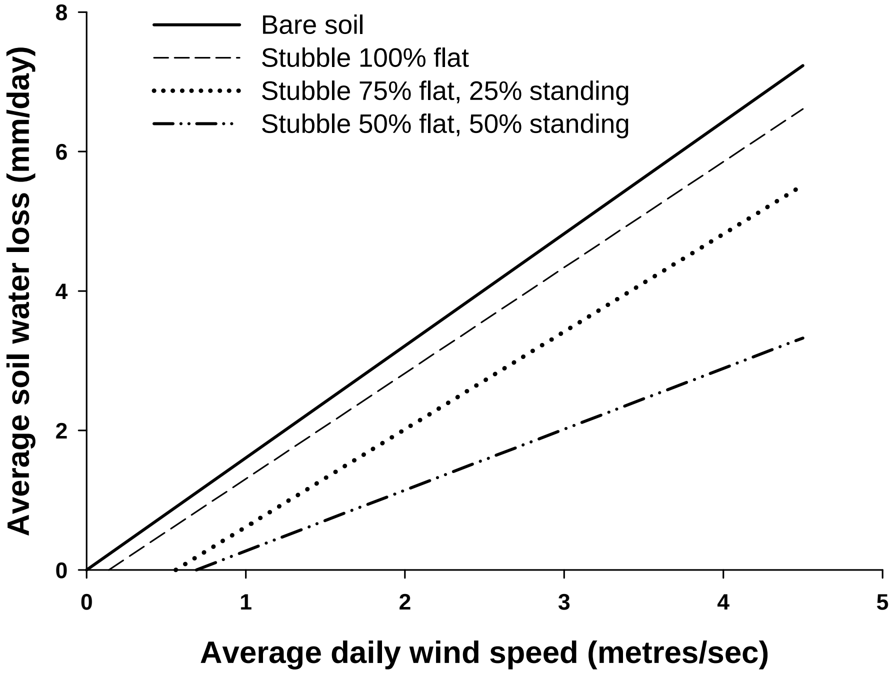

Figure 12. The effect of wind speed on soil moisture loss from bare soil and soil with different stubble coverage. Source: Smika (1983), reprinted with permission[12].

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[11] ©Soil Science Society of America (1983), 2 Sept 2009
[12] ©Soil Science Society of America (1983), 2 Sept 2009

Table 5. Average daily soil water loss and average daily soil surface temperature as affected by bare soil and straw position during a 5 week August-September period without precipitation.

Straw position	Daily soil water loss (mm)	Surface soil temperature (°C)
Bare soil	0.66	47.8
100% straw flat, 0% standing	0.56	41.7
75% straw flat, 25% standing	0.53	39.6
50% straw flat, 50% standing	0.43	32.2

Source: Smika (1983), reprinted with permission[13].

2.2.3 Soil moisture storage

Soil moisture storage was significantly higher at the end of fallow periods in Queensland when stubble was retained rather than removed (Table 6). In no-till treatments, where stubble was left standing, compared with stubble removal, the increase in stored soil moisture during the fallow period was either 27 or 30 mm (central Queensland and southern Queensland, respectively, Table 6). When stubble was partially incorporated by conventional cultivation, the presence of stubble increased moisture storage by 17 or 7 mm (central Queensland and southern Queensland, respectively). The retention of stubble in these systems would advantage a subsequent crop through greater stored soil moisture.

Table 6. The stored soil moisture at sowing under a range of fallow and stubble treatments in central and southern Queensland.

Fallow treatment	Available soil moisture at sowing (mm)	
	Central Queensland[1]	Southern Quensland[2]
No-till/ stubble removed	225	109
No-till/ stubble retained	252	139
Reduced tillage/ stubble removed	n.a.	116
Reduced tillage/ stubble retained	n.a.	129
Conventional cultivation/stubble removed	195	117
Conventional cultivation/stubble retained	212	124

[1] Mean of 11 seasons; 1.5 m depth; stubble removed by burning after harvest, (Marley and Littler, 1989).
[2] Mean of 10 seasons; 1.2 m depth; stubble removed after harvest (Radford et al., 1992; Thomas et al., 1995).

Other research in Queensland (Felton et al., 1987; Freebairn and Wockner, 1983) indicated that stubble increased soil moisture storage by reducing surface runoff, rather than by reducing evaporation (Figure 13). In this example, a stubble mulch layer over a cultivated seedbed did not influence total evaporative losses when averaged over 4 fallow seasons. The authors suggested that stubble mulch was only likely to increase soil moisture storage when rainfall events were frequent or when the amount of stubble mulch was high (10-15 t/ha). Experience in southern NSW with a 6 t/ha stubble showed evaporation was reduced by 10 mm in the first 24 hr after a simulated rainfall event in February, but had no effect on soil moisture storage 16 days after the "rainfall" event (Cornish, 1987b) (PS Cornish cited by Felton et al., 1987). The effect of stubble retention then was to increase soil moisture storage by reducing surface runoff and slowing evaporative loss, compared with the absence of stubble cover. However, reductions in surface runoff can be achieved with less stubble cover

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[13] ©Soil Science Society of America (1983), 2 Sept 2009

than would be required to reduce evaporative losses. Hence, in the Queensland study, the inability of stubble to reduce evaporative losses may be explained by stubble loads that were too low to influence evaporative loss.

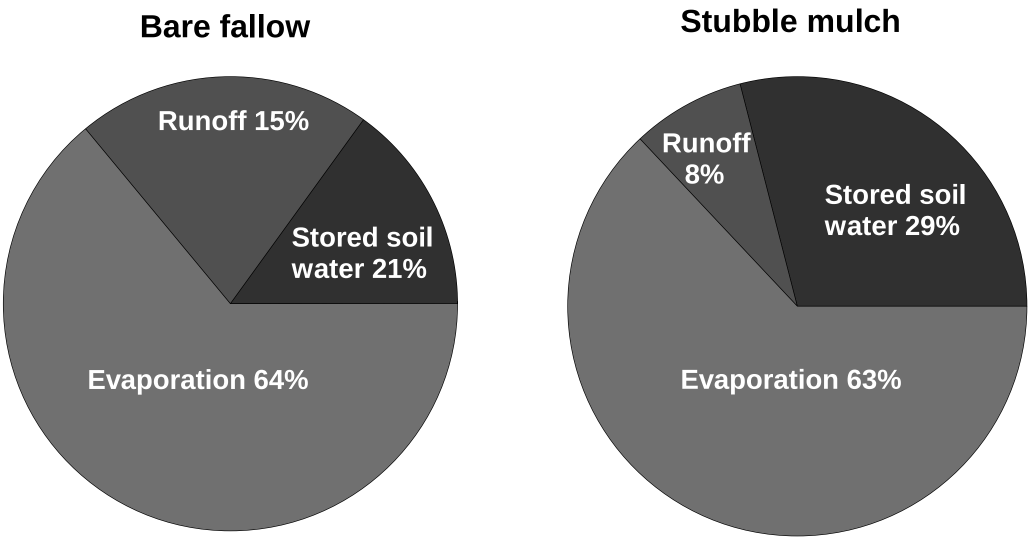

Figure 13. Summer water balance for bare fallow and stubble mulch (sweep tillage) at Greenwood 1978/79-82/83 on a grey clay soil with mean fallow rainfall (December to June) of 440 mm. Source: Felton et al. (1987), republished with permission[14].

The major effect of stubble retention on soil moisture storage, under Australian conditions, may have been due to increased rainfall infiltration rather than reduced evaporation. However reduced evaporative loss of soil moisture due to stubble retention can have a short-term effect, depending on the frequency and pattern of rainfall, and may be useful for improving crop establishment.

In southern Australia the presence of stubble during summer increased storage of soil moisture at sowing. At Wagga NSW stubble loads of 0-14 t/ha were established by stubble removal and addition soon after harvest (Cornish, 1987b; Cornish and Lymbery, 1986). Soil moisture storage by May was maximised by about 5 t/ha of stubble, following rainfall of 140 mm between December and May and an additional 35 mm of “simulated” rainfall during February (Figure 14) At Merredin WA, soil moisture storage in April was measured after establishing plots in February of burnt or standing stubble and 0, 2, 4 and 8 t/ha of applied straw, and watering with 50 mm sprinkler applied “rain” (Hamblin et al., 1987; Perry et al., 1992). Plots with burnt stubble retained about 14 mm of stored moisture (28% of water applied) and this increased to 23 to 26 mm with the straw applied treatments. Interestingly the standing stubble (amount not stated) retained 27 mm of stored water.

Current farmer practice of retaining stubble until just prior to sowing was, therefore, likely to preserve some soil moisture. If the burning of stubble took place within about 4 weeks of sowing, the effects on stored soil moisture of stubble retention would be less than indicated by results reported from Queensland, Wagga Wagga (Cornish, 1987b; Cornish and Lymbery, 1986) or Merredin (Hamblin et al., 1987; Perry et al., 1992), where the stubble was either burnt or removed soon after harvest. Additionally, crop growth in Queensland and northern NSW was more dependent on stored soil moisture from summer dominant rainfall as

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[14] ©Australian Society of Agronomy (1987), 17 Sept 2009

compared with the southern cropping areas where rainfall was either non-seasonal or winter dominant, and incident rainfall during the crop growing season was the major contributor to water supply (Thomas et al., 2007). However, additional stored moisture achieved through stubble retention over summer-autumn would be expected to improve crop establishment and increase grain yield.

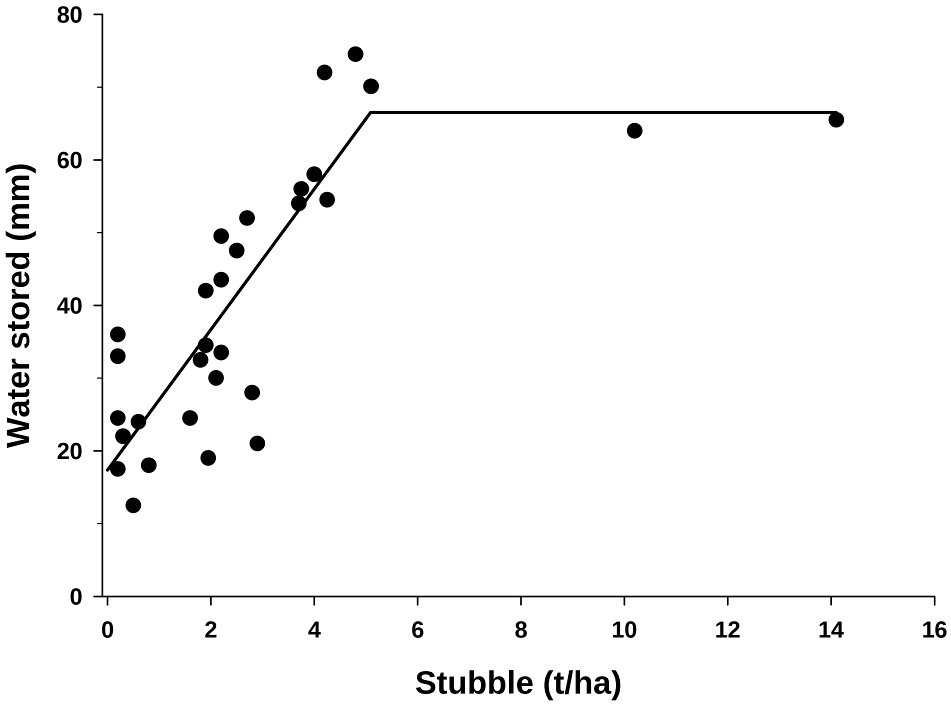

Figure 14. Soil moisture storage at Wagga Wagga NSW in May 1985 under a range of stubble loads following 140 mm of rain, and 35 mm of additional irrigation. A two phase linear model has been fitted to the data. Source: Cornish (1987) republished with permission[15], Cornish and Lymbery (1986).

Retention of stubble on the soil surface increased surface moisture at sowing time, and allowed an earlier and/or an extended time window for sowing, particularly in dry seasons (Radford and Nielsen, 1983). At one site (Acland, Queensland) the presence of wheaten stubble maintained sowing conditions for wheat for more than 22 days compared with 17.5 days with no stubble mulch. Again moisture for sowing in the southern cropping areas was more reliable than in Queensland. However, in a survey of 700 farmers in southern NSW (Davis, 2006) "conserving soil moisture" was identified as an advantage of stubble retention by 75% of respondents. It was not clear whether farmers were identifying stored soil moisture or surface moisture conditions at sowing, or both as perceived advantages of stubble retention. Further, at Wagga Wagga in both 1989 and 1990, higher moisture content was identified in the surface 10 cm of soil due to stubble retention compared with late stubble burnt treatments (Chan and Heenan, 1996).

Greater storage of soil moisture, leading to increased storage at depth, can have a positive impact on grain yield as the crop may access this moisture late in the growing season, during grain fill (Kirkegaard et al., 2007). Greater storage of soil moisture under retained stubble can also have adverse effects under some circumstances. Kirkegaard et al. (2001) measured up to

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[15] ©Australian Society of Agronomy (1987), 15 Sept 2009

70 mm of stored moisture at harvest, but in the following wetter season this led to deep drainage below 1.1m depth, and 77 mm of water were lost to crops as compared with 25 mm in the cultivated and stubble burnt treatment. Leaching of water below the rooting depth of crops may lead to rising water tables, wetness or salinisation in parts of the landscape (Eberbach, 2003), and loss of nitrate which exacerbated acidification of soil (Helyar and Porter, 1989). Early growth was reduced and grain yield was lower in the stubble-retained, direct drilled system and it has been suggested that poor plant growth may have contributed to greater soil moisture loss by deep drainage (Kirkegaard et al., 2001).

Soil moisture storage at sowing was increased by long fallow at Dooen, Victoria by an average 76 mm, as compared with a short fallow (O'Leary and Connor, 1997). Retaining stubble added a further 52 mm (range 36–65 mm). At Walpeup, with lower rainfall and lighter textured soil, long fallow increased moisture storage by an average of 37 mm as compared with short fallow, and stubble added 27 mm in only one year of four. The additional moisture stored in the experiments was deep in the soil profile, the long fallows were of 18 months duration and atypical of present cropping systems. However, simulation studies using long-term rainfall records indicated that stubble retention increased soil moisture storage at the end of the fallow period by 89 mm at Dooen and 25 mm at Walpeup, and produced grain yield increases of 0.8 t/ha at Dooen and 0.6 t/ha at Walpeup (O'Leary and Connor, 1998). Related simulation studies on the Dooen site (O'Leary, 1996) indicated deep drainage of an additional 18.5 mm/year of recharge in the stubble-retained, no-tillage treatment, compared with the cultivated, no stubble treatment. Although, these data result from a protracted 18 month fallow, they indicated that increased soil moisture storage at sowing, combined with a wet season, can produce problems with deep drainage of moisture and an increased potential for resultant salinisation and acidification.

Stubble retention was likely to increase soil moisture storage at sowing and this effect in Australia was likely to be due to increase moisture infiltration rather than reduced evaporation from the soil. Increased moisture available to the crop was an advantage in the more northerly cropping areas (northern NSW and Queensland) where there was a high reliance for winter crop growth on stored moisture from summer. This advantage may have been relevant in winter dominant rainfall areas when rainfall in the cropping season was low. However, in higher rainfall southern areas, with their high winter rainfall, increased moisture storage at sowing could become a disadvantage when this increased deep drainage of water.

2.3 Reduced Spread of Disease

At four sites in WA, infection of lupin leaves with brown leaf spot (*Pleiochaeta setosa* [Kirchn.] Hughes) was significantly lower when cereal stubble mulch was retained compared with removal of mulch (Sweetingham et al., 1993). The protection offered by mulch appeared to be greatest for leaves higher in the canopy, which was expected as brown leaf spot of lupin was initiated by soil borne spores transferred onto leaves by rain splash; cereal stubble mulch would have limited rain splash. Protection against disease incidence was highest when mulch was used in combination with fungicide, as the fungicide also reduced disease incidence in lower leaves (Sweetingham et al., 1993). These authors found that even a small amount of stubble (10% cover, 0.5 t/ha) gave some benefit, while optimal benefit was at 2 t/ha of stubble. The advantage of stubble retention in reducing brown leaf spot was supported by observation in southern NSW (Simpfendorfer et al., 2004).

The spread of cucumber mosaic virus (CMV) in lupins can be slowed by the presence of cereal stubble. When lupin seed with 5-15% infection by CMV was sown, the spread of the disease was reduced where cereal stubble was spread (Bwye et al., 1999). The final incidence of CMV infection at 4 sites was reduced by 25-40% with stubble mulch, and 4 t/ha of stubble gave a lower incidence than 2 t/ha. These authors suggested that retaining stubble was the most effective of the management strategies they tested, because it had greatest effect before canopy closure, and its effect carried throughout the growing season. CMV was spread by aphids, and aphid numbers were lower with retained stubble. Stubble appeared to function by decreasing the landing of aphid vectors.

2.4 Conservation of Nutrients

Stubble retention can retain some nutrients in the cropping system. The extent of nutrient losses with stubble removal can be estimated from knowledge of nutrient concentrations in stubble and stubble amount. Stubble contains approximately 15% of the N and P, 36% of the S and 80% of the K present in wheat at maturity (Whitbread et al., 2000). Typical concentrations of nutrients in wheaten stubble are given in Table 7.

Table 7. The concentration of nutrients in straw of wheat after harvest.

Reference	Locality	Crop	Nutrient concentration (%)			
			N	P	K	S
(Schultz and French, 1976)	South Australia	Wheat[1]	0.51	0.05	1.28	0.13
(Pearce et al., 1979)	Victoria	Wheat[2]	0.42	0.08	0.63	n.a.
(Heard et al., 2006)	Manitoba, Canada	Spring wheat[3]	0.97	0.14	1.44	0.11

[1] mean of 42 samples
[2] mean of 16 samples
[3] mean of 3 samples

Based on the values in Table 7, the removal of 1 t/ha stubble of wheat would remove 4-10 kg N/ha, 0.5-1.4 kg P/ha, 6-14 kg K/ha and 1.1-1.3 kg S/ha. These nutrients were kept in the nutrient cycle when stubble was retained, although availability depended on the extent and rate of stubble decomposition. In addition, immobilisation of N during stubble decomposition could limit N supply in the short term. However this temporary tie-up of nutrient was not equivalent to the absolute loss of nutrient from an autumn stubble burn, as practised widely in the southern Australia cropping areas.

Stubble losses between harvest and sowing in NSW ranged from 25-35 % (i.e. 65-75% of stubble remaining, Burgess et al., 1993; Doube et al., 1994), where the stubble was undisturbed. Where stubble was grazed by sheep, 66-72% of stubble remained at sowing (Mulholland et al., 1976b). Thus, sheep intake was minor and the major stubble loss may have been due to stubble decomposition resulting from rainfall. The results indicated that 25-33% of stubble present at harvest had been returned to the soil by late autumn. It was also possible that a far higher proportion of N in the stubble was lost to the soil over summer/autumn. This could be due to the stubble components highest in N concentration (leaf and glume) being decomposed faster than the straw. Further, mature but un-leached cereal straw contains a water soluble fraction. When cereal straw was leached with hot water (Harper and Lynch, 1982), wheat and barley lost 8.5% by weight, and oat, 11.8%. The extracts were 27-36% C and 1.5-2.3% N, representing 5.2-9.7% of the total C, 46-64% of the total N in the straw. That is, about half the N in cereal stubble can be extracted using hot water; similar amounts can be extracted in cold water (Rice, 1979).

The total loss of N (kg/ha) over summer from oaten stubble was greater (64%) than the loss of stubble weight stubble (26%) at Ginninderra (Australian Capital Territory, ACT, Mulholland et al., 1976a). At Condobolin, the amount of N lost from wheaten stubble was 35% compared with an 18% loss of stubble weight (Mulholland and Coombe, 1979). This pattern was not consistent across locations. For example, at Walpeup, Victoria, N concentration in wheaten stubble remained constant in a wet summer/autumn season (Robertson, 2002). The possibility of N being lost from stubble more rapidly than the weight of stubble over summer/autumn seemed possible, under some circumstances. The fate of the lost N was not understood, however the process would widen the C/N ratio of the remaining stubble, which may decrease its rate of decomposition.

When stubble was burnt, the oxides of C, N and S were presumably lost as gases while the solid oxides (e.g. K_2O, CaO, MgO, P_2O_5) mainly remained in the ash. The ash component has been recorded as 7–15.2% of wheaten straw (Gullett and Touati, 2003) and 13% (Heard et al., 2006). However, the separation of the fate of nutrients in a burn, based on their likely gaseous or solid form, does not appear to be reliable (Table 8). High losses of solid oxides were recorded following a single hot burn in the field (Angus et al., 1998). The "cold burn" of Angus et al. (1998) on a single sample of straw and that of Heard et al. (2006) on 3 samples were conducted as burns in the open in metal containers, and had lower losses of the solid oxides. No further reports of Australian data on burns in the field were identified in addition to Angus et al. (1998).

The losses of N (82-88%; mean 85%) and S (65-81%; mean 74%) were reasonably consistent (Table 8). However, the loss of solid oxides varied widely. It was probable that this was due to the vigour of the fire and the resultant convection producing different losses of the solid ash component. The loss of ash was estimated by averaging across the solid ash nutrients (Table 8). Further losses may occur, due to subsequent wind and water wash removing ash from the paddock. While airborne ash, containing the solid oxides, may be lost from the burnt paddock, it may deposit in neighbouring paddocks. Where stubble burning was a widely adopted practice for stubble management, much of the ash lost during burning would be returned to the soil but redistributed across paddocks.

Table 8. Estimates of nutrients loss (%) from straw due to burning - nutrients present in the straw which were not recovered in the ash after burning.

	Loss (%)			
	Theoretical[1]	Angus et al. (1998) (cold burn)	Heard et al. (2006)	Angus et al. (1998) (hot burn)
Carbon	100	nr[2]	92	nr
Nitrogen	100	88	85	82
Phosphorus	0	0.4	10	44
Potassium	0	0	11	40
Sulfur	100	75	65	81
Calcium	0	8	nr	52
Magnesium	0	2	nr	47
Suggested loss[3]	0	2.6%	10.5%	46%

[1] Assumed from oxides of N, S and C being gases, and other oxides being solids.

[2] nr = not reported.

[3] Suggested loss due to ash loss by convection (mean of solid oxides).

The loss of K was consistent with the analysis of fine particulates conducted by Hays et al. (2005). Sulphur content of particulates was low (2.35%) and 80% of sulphur occurred as sulphate. The particulates ($PM_{2.5}$) contained 31% by weight of K, most of which was soluble in water. The assumption would be that the K was in the form of K_2O, but there may have also been a large amount of KCl. The $PM_{2.5}$ fraction would account for a concentration of 0.147% K in the original stubble (not measured), which represents about 10% of the K in typical stubble (Table 9). No Ca or Mg was detected in the particles.

Australian data from northern NSW averaged over 3 seasons showed that 9% of stubble remained after burning (Burgess et al., 1993). In southern NSW, in one instance, 8% of stubble remained after burning (Doube et al., 1994).

A typical picture of nutrient losses from burning wheaten stubble at Condobolin and Wagga Wagga (NSW) is shown in Table 10. The estimates of stubble amount at harvest were derived (Condobolin, 20 years, Fettell, unpublished) or measured (Wagga Wagga, 27 years, Heenan, unpublished) in long-term experiments, with an assumed stubble reduction over summer of 1 t/ha. Nutrient concentration in the stubble was based on Schultz and French (1976). Losses from burning were estimated to be 85% of N, 74% of S, all other nutrients of 15%, with 10% of stubble remaining unburnt. The greatest loss was of N with smaller losses of K and S. The practice of burning on an ongoing basis caused greater depletion of some major nutrients than stubble retention. These depleted nutrients would need to be replaced, at some cost, by fertiliser inputs.

Table 9. Analysis of particulate emissions ($PM_{2.5}$) from burning of stubble of wheat and rice.

	Emission factor (g/kg)	
	Wheat straw	Rice straw
$PM_{2.5}$ mass	4.71 ± 0.04	12.95 ± 0.30
Organic carbon	1.23 ± 0.03	8.94 ± 0.42
Elemental carbon	0.52 ± 0.00	0.17 ± 0.04
Elements	Mass fraction of $PM_{2.5}$ mass (%)	
Na	1.64 ± 0.58	
S	2.35 ± 0.21	0.28
Cl	35.66 ± 2.83	1.6
K	31.30 ± 1.72	0.57
Br	0.39 ± 0.03	
Water-soluble		
Cl	24.22 ± 0.66	1.65 ± 0.01
NO_3^{2-}	0.29 ± 0.01	ND
SO_4^{2-}	5.43 ± 0.74	0.47 ± 0.01
NH_4^+	1.78 ± 0.19	ND
K^+	24.57 ± 0.39	0.58 ± 0.01
Ca^{2+}	ND[1]	ND
Mg^{2+}	ND	ND

Source: Hays et al. (2005), reprinted with permission[16].

[1] ND = not detected.

These estimates of annual losses of nutrients were relatively small and less than those estimated by implying complete loss of all nutrients (Early et al., 1997), or from a hot burn of heavy stubble (Kirkby, 2002). At Wagga Wagga, loss of N of 26 kg/ha/year was estimated for burning of wheaten stubble (Table 10). However long-term estimates of total soil N (Heenan et al., 2004) show that in a wheat/lupin rotation with direct drilling, the stubble retention treatments lost total soil N at 13 kg/ha/year, while stubble burning lost N at 28 kg/ha/year; the difference between stubble retention and late stubble burning in that system was about 15 kg/ha/year.

Table 10. The amount of nutrients (kg/ha) lost by late burning wheaten stubbles prior to sowing at Condobolin (2.34 t/ha stubble) and Wagga Wagga (6.59 t/ha stubble) in NSW. Values are means with (ranges)[1].

Nutrient	N	P	K	S	Ca	Mg
Condobolin	9.1 (2.8-20.6)	0.2 (0.1-0.5)	4.1 (2.2-8.1)	2.0 (1.3-3.2)	0.6 (0.3-1.2)	0.5 (0.3-0.8)
Wagga Wagga	25.7 (8.0-58.0)	0.5 (0.2-1.3)	11.4 (6.1-22.7)	5.7 (3.5-9.2)	1.6 (0.9-3.4)	1.3 (0.8-2.3)

[1] Refer to text for data and assumptions.

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2.5 Avoidance of the Smoke Hazard from Burning

When stubble was retained, the adverse effects of burning were avoided. These effects included the introduction of smoke into the atmosphere and its potential impact on human health. However, even with adoption of conservation farming practices it may be necessary to burn stubble opportunistically to maintain production (see disadvantages of stubble retention in Table 2) and so an understanding of the potential health hazards and possible measures for mitigating hazards was considered relevant in the current monograph.

Smoke from biomass burning contained mainly carbon dioxide and some carbon monoxide (CO), nitrogen dioxide (NO_2), and numerous volatile organic compounds and particulate matter. Fine particulates with a diameter less than 2.5 µm ($PM_{2.5}$) can have a detrimental impact on human health from both acute and chronic exposures (Pope et al., 1995), and some of the organic compounds produced (eg polycyclic aromatic hydrocarbons) were considered carcinogenic.

The products of combustion varied depending on a range of factors. $PM_{2.5}$ emissions varied from 3.0-8.5 g/kg of fuel for the burning of wheaten stubble under a range of conditions (Table 11, Dhammapala et al., 2006). Additional data on $PM_{2.5}$ emissions for wheat stubble were 4.71±0.04 g/kg (Hays et al., 2005) and 6–11 g/kg (Anon, 1995). This variability was influenced by combustion efficiency (Dhammapala et al., 2006) and flaming or smoldering burn (Zarate et al., 2000). Total particulate matter (TPM) was greater with smoldering burns than with flaming burns (Zarate et al., 2000). These in turn were influenced by oxygen supply, size and type of fuel load, fuel chemistry and moisture, alkali metal content and firing technique (Hays et al., 2005). The distribution of the smoke plume, and hence its impact on centres of population, would depend on topography and meteorological conditions (e.g. wind direction, inversion layers).

Table 11. Emission factors (g/kg) and emission ratio from burning wheaten stubble.

Reference	Emission component			
	$PM_{2.5}$	CO	Total Hydrocarbons	$PM_{2.5}$/CO ratio
(Dhammapala et al., 2006)	3.0 ± 0.6	52.9 ± 8.0	2.2 ± 0.4	0.05 ± 0.01
(Dennis et al., 2002)	4.2	38.2	2.9	-
(Schaaf, 2003)	3.6 ± 0.7	44.1 ± 7.4	-	0.08 ± 0.01
(Turn et al., 1997)	5.6	-	-	-
(Anon, 1995)	8.5	59	-	-
(Zarate et al., 2000)	-	35	-	0.07

Adapted from: Dhammapala et al. (2006).

Measurement of the chemical constituents of the $PM_{2.5}$ (Hays et al., 2005) showed that it was predominantly carbon (C) at 42% (Table 9). This carbon was 70% organic C, and 30% elemental C. Potassium (31 %) and chloride (36%) were the other major elemental contents.

In the study of Hays et al. (2005), stubble burns were of short duration. Within two to three minutes temperature peaked in a flame burn, above the fire and in the fire bed (Figure 15, Hays et al., 2005) with peak temperatures of 275–300°C in the fire bed and 150-175°C over the fire recorded. Peak CO_2 and minimum O_2 concentrations in the air occur within about 1 minute of this peak temperature, while CO peak concentrations were delayed a further one to two minutes and occur in the smouldering burn phase. Particulate matter emissions also peaked in the smouldering burn (Figure 16, Zarate et al., 2000).

Human exposure to smoke may be minimised by changes in the control of stubble burning. Currently, a farmer wishing to burn stubble at a time of fire risk (summer and commonly early autumn) must seek a permit from the local fire captain. This process was targeted at minimising the risk of bushfire. Permission to burn may be refused, or made conditional on the availability of fire fighting equipment at the site at the time of burning. Later in the season burning was unconditional when fire risk season closed (generally March 31st). Additional suggestions for reducing human exposure may be to prescribe the method of burning and/or to deny permission based on meteorological condition (i.e. inversions, wind direction or strength) which may slow smoke dispersal. Emissions were not different using head burning (lighting the upwind edge of the paddock), back burning, strip burning head fires and mass ignition (lighting the entire perimeter of the paddock as rapidly as possible, Schaaf, 2003). Locally, a 'draw' burn (the mass ignition system of Schaaf, 2003) was suggested, as this created a more rapid, concentrated fire where the smoke rose high and dispersed. With this system total emissions would be expected to be similar, but dispersion may be hastened.

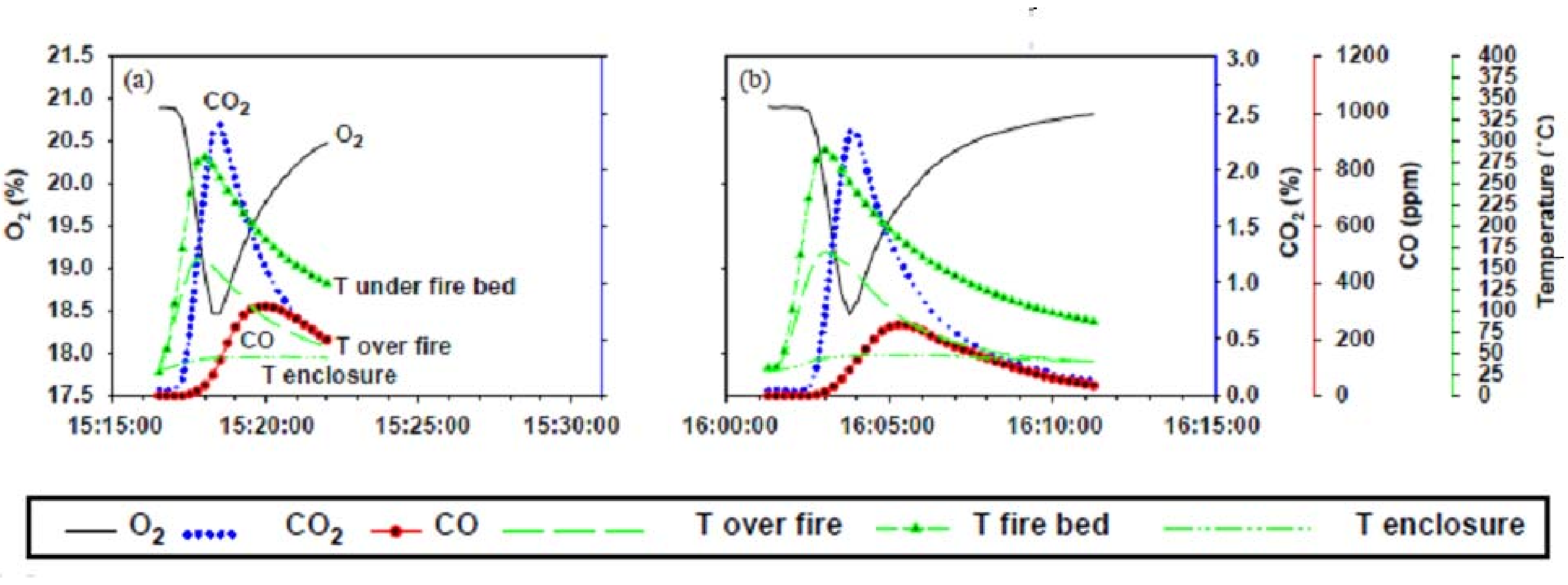

Figure 15. Continuously measured CO_2, O_2, and CO concentrations and fire zone temperatures for two representative test fires (a and b) with wheaten straw in a combustion chamber. Source: Hays et al. (2005), reprinted with permission[17].

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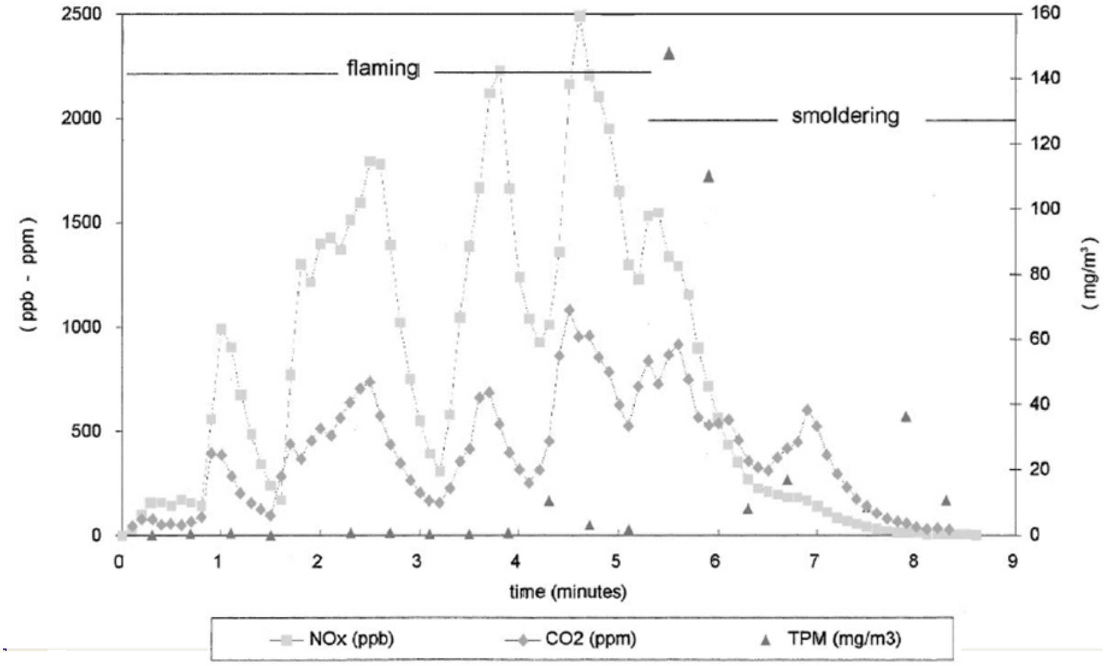

Figure 16. Temporal evolution of CO_2, NO_x and total particulate matter (TPM) concentrations during of field burning. Source: Zarate *et al.* (2000), reprinted with permission[18].

2.6 Soil Organic Carbon (SOC) Accumulation

When stubble was retained and soil disturbance minimised, the percentage of SOC was generally higher in the surface soil than where stubble was removed or burnt and soil tilled. This higher SOC level influenced the characteristics of the surface soil. However, this did not imply that the amount of SOC (t/ha) increased with time under conservation farming (i.e. that C was sequestered). In many instances the rate of decline of SOC (t/ha) was merely less where stubble was retained.

Monitoring of SOC% can be misleading of parallel changes in soil bulk density and distribution of SOC in the soil profile under different management systems. Effects on the depth of soil sampling when comparing treatments can further complicate interpretation and need comprehensive information to estimate correction (see Ellert and Bettany, 1995; Skjemstad and Spouncer, 2003). In these papers, SOC amount (t or kg C/ha) has been estimated from SOC% and adjusted for bulk density changes, but not for soil sampling depth.

A long-term study at Wagga Wagga (Heenan et al., 2004) was initiated following 19 years of subterranean clover pasture (Table 12). The lupin/wheat rotation (L/W) with retained stubble and direct drill sowing (DD, rotation 1) was stable for both organic C (loss of 8 kg C/ha.yr, not statistically significant) and total N (loss of 13 kg N/ha.yr, not statistically significant). If stubble was not retained, SOC was lost at 138 kg C/ha.yr, and if conventional cultivation (CC, multiple pass cultivation) was used and stubble retained (i.e. stubble incorporated) the SOC loss was 199 kg C/ha yr. In contrast, one year of subterranean clover and one year of wheat with no stubble burning was stable using CC, and was SOC accretive using DD. Burning of stubble in this rotation would damage the subterranean clover seed carried over and was of no

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advantage as a crop was not sown in the year following wheat. The conclusion was that continuous cropping systems can be sustainable over 21 years with conservation tillage systems, while systems using a subterranean clover based pasture-crop system were stable to accretive for SOC.

Table 12. Average linear slope of soil organic carbon (SOC) and total nitrogen (N) in the surface (0-10 cm) over 21 years at a site at Wagga Wagga, NSW.

Rotation[1]		Stubble management	Tillage[2]	Soil Organic Carbon Average slope (kg C/ha.yr)	Soil Organic Carbon T value[3]	Total soil N Average slope (kg N/ha.yr)	Total soil N T value[3]
1	L/W	Retained	DD	−8	NS	−13	NS
2	L/W	Retained	CC	−199	***	−29	***
3	L/W	Burnt	DD	−138	**	−28	***
4	L/W	Burnt	CC	−284	***	−42	***
5	W/W	Burnt	CC	−389	***	−51	***
6	W/W(+N)	Burnt	CC	−311	***	−42	***
7	S(grazed)/W	Retained	CC	−72	NS	−13	NS
8	S(slashed)/W	Retained	DD	+185	***	+9	NS
9	S(slashed)/W	Retained	CC	−4	NS	−6	NS

Source: Heenan et al. (2004), reprinted with permission[19].

[1]L = lupins; W = wheat, S = subterranean clover.

[2]DD = direct drilled, CC = three pass tillage.

[3]NS = not significant ($p > 0.05$), **$p < 0.01$, ***$p < 0.001$.

Soil organic carbon amounts in the surface soil (0-10 cm) for a wide range of experiments conducted on conservation tillage in southern Australia have been reviewed (Table 13, Chan et al., 2003). Measurements were made following different durations of the experiments. Many sites showed no differences between the amounts of SOC from practising conservation as compared with conventional tillage. The organic carbon in the 0-10 cm soil (Figure 17) in the conventional and conservation tillage systems in the wheat cropping areas (i.e. excluding Grafton) were related and did not deviate significantly from the 1:1 line. The ratio of SOC in the two systems of farming was related to rainfall (r = 0.73, Chan et al., 2003). This relationship was due mainly to the Grafton site (1057 mm annual rainfall) which had higher rainfall and higher SOC storage in the soil under direct drilling compared with conventional cultivation. The southern Australian data were also different from data from the USA (Kern and Johnson, 1993, cited by Chan et al., 2003).

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Table 13. Differences in soil organic carbon (SOC) under conservational tillage compared with conventional tillage for light-textured soils at different locations in southern Australia.

Source	Location[1] (Rainfall, mm)	Soil	Treatment[2]	Duration (years)	SOC
Chan and Mead, (1988)	Cowra, NSW (564)	Red duplex (Dr 2.62)	DD-SR v. CT-SB	3	Higher
Heenan et al. (1995)	Wagga Wagga, NSW (550)	Chromosol, sandy loam Red earth (Gn 2.12)	DD-SR v. CT-SB	14	Higher
Packer et al. (1992)	Cowra, NSW (564)	Kandosol, clay loam Red duplex (Dr.3.22)	DD-SR v. CT-SB	7	Higher
Packer et al. (1984)	Ginninderra, NSW (633)	Chromosol, sandy loam Red podzolic	DD-SB v. CT-SB	5	Higher
Cavanagh et al. (1991)	Forbes, NSW (527)	Kurosol, sandy loam Red-brown earth (Dr 2.23)	DD v. CT	3	Higher
Carter et al. (1994)	Rutherglen, Vic (593)	Chromosol, sandy loam Yellow duplex (Dy 3.33)	DD-SR v. CT-SB	10	Higher
Grabski et al. (1997)	Grafton, NSW (1057)	Kurosol, sandy clay loam Podzolic	DD-SR v. CT-SR	14	Higher
Burch et al. (1986)	Lockhart, NSW (430)	Kurosol, loam Red-brown earth,	DD-SR v. CT-SB	3	No difference
Fettell and Gill (1995)	Condobolin, NSW (430)	Sodosol Red-brown earth (Dr 2.13)	DD-SR v. CT-SB	14	No difference
Jarvis (1996)	Merredin, WA (287)	Chromosol, clay loam Red-brown earth	DD-SR v. CT-SR	19	No difference
Roget (pers. comm.)	Avon, SA (350)	Sodosol, clay loam Calcareous sandy loam	DD-SR v. CT-SR	15	No difference
Roget (pers. comm.)	Kapunda, SA (500)	Red-brown earth Chromosol/Sodosol, loam	DD-SR v. CT-SR	11	No difference

Source: Chan et al. (2003), reprinted with permission[20].
[1]Vic = Victoria.
[2]DD = direct drilled, CT = multi pass tillage, SR = stubble retained, SB = stubble burnt.

Chan et al. (2003) concluded that in most of the cereal cropping areas in Australia (rainfall of 250-600 mm) the potential for conservation tillage to store carbon and mitigate green house gas emission was limited, in contrast to areas with higher rainfall and greater biomass production. Chan et al. (2003) suggested a threshold of 500 mm of annual rainfall; at rainfall greater than this the effects of conventional and conservational farming systems on SOC storage begin to diverge.

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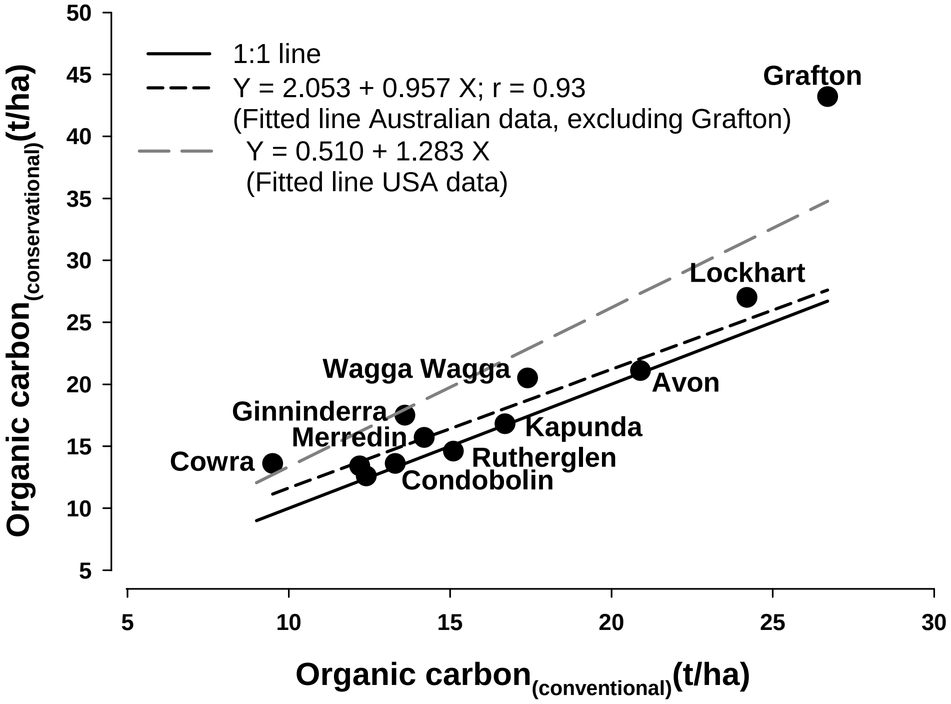

Figure 17. Relationship between soil organic carbon (SOC) in the 0-10 cm soil under conventional versus conservational tillage in experiments on light textured soils in southern Australia. Source: Chan et al. (2003), reprinted with permission[21] with an added fitted line for data shown (excluding Grafton, short dash) and an added fitted line for USA data (long dash).

Six of the experiments conducted in the wheat belt showed increased SOC amount under conservational farming (Table 13). In the case of the Wagga Wagga site (Table 12) the difference was the result of a near stable SOC in the direct drilled, stubble-retained system, and a loss of SOC in the conventionally tilled and stubble burnt system. At Ginninderra (Packer et al., 1984) and at Cowra (Chan and Mead, 1988) all tillage systems had SOC levels in the 0-10 cm soil which were less than a nearby permanent pasture soil. At one Cowra site (Packer et al., 1992), where measurements of SOC% and bulk density were made over 7 years, estimates showed organic carbon storage declined under conventional tillage and stubble burning, while direct drilling and stubble retention maintained SOC (slope not statistically significant, Figure 18).

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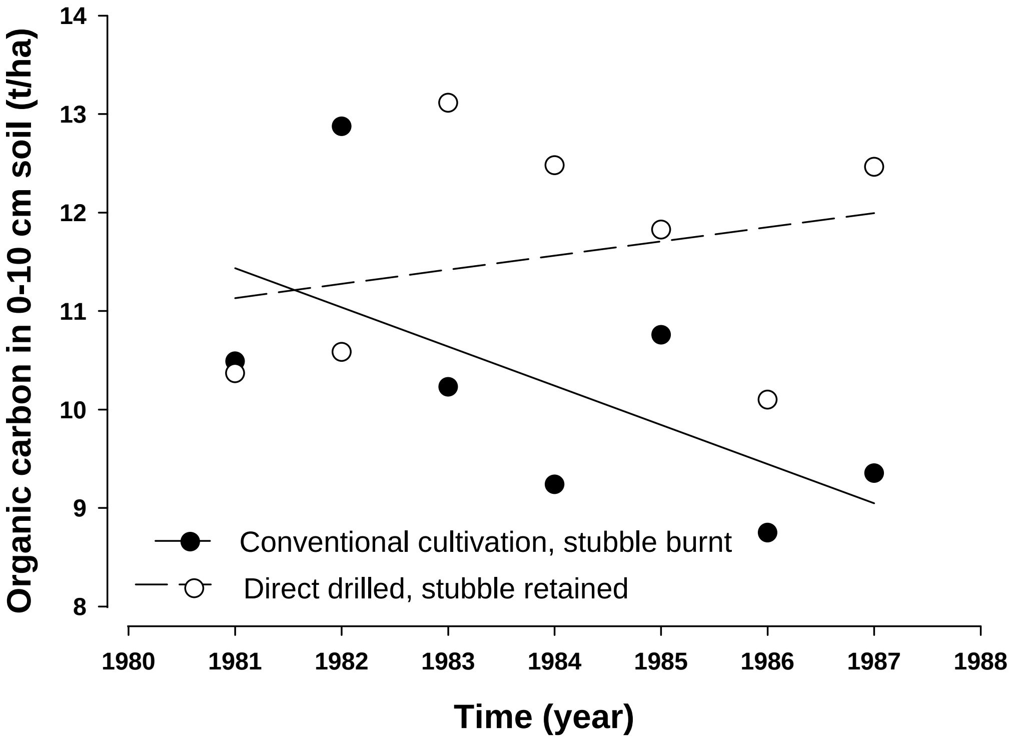

Figure 18. Change in organic carbon storage over seven years with either a conventional tilled stubble burnt or direct drilled stubble retained conservational farming system at Cowra, NSW. Adapted from: Packer et al. (1992).

The effect of tillage versus stubble retention on SOC could be separated only in one experiment conducted at Wagga Wagga, NSW. In a subsequent paper on the same experiment (Chan and Heenan, 2005) total carbon present in the 0-10 cm depth after 19 years of the experiment were reported. The effect of tillage (DD vs CC) and stubble (retained vs burnt) were statistically significant, but there was no significant interaction (Table 14). Chan and Heenan (2005) concluded that the negative effects of tillage (direct drilling vs conventional cultivation) on total carbon were greater (5.95 t/ha of C) than the effects of stubble management (retained *vs* burnt; 1.75 t/ha of C). In these continuous cropping treatments there was no sequestering of carbon; carbon was lost at different rates with the smallest loss (not different from nil loss) in the DD stubble-retained system (Table 12).

Table 14. Total carbon (t/ha) in the soil (0-10 cm) in a lupin/wheat cropping sequence after 19 years at Wagga Wagga, NSW.

Stubble management	Tillage treatment[1] DD (t/ha total C)	CC (t/ha total C)	Stubble means (t/ha total C)	Stubble Difference (t/ha total C)
Burnt	24.1	17.7	20.90	1.75
Retained	25.4	19.9	22.65	
Tillage means	24.75	18.80		
Tillage difference	5.95			

Source: Chan and Heenan (2005), reprinted with permission[22].
[1]DD = Direct drill, CC = three pass tillage.

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Both DD and stubble retention maximised the amount of SOC in the shallow soil surface (0–5 cm). For example, after 10 years of a wheat/lupin system at Wagga Wagga NSW (Chan et al., 1992) there were greater amounts of SOC and concentrations of total nitrogen in the 0-5 cm layer due both to stubble retention compared with stubble burning (1.98 t/ha of OC and 0.03% total N) and to direct drilling compared with conventional tillage (4.26 t/ha and 0.05 % N; Table 15). This resulted in greater potential microbial activity and a more stable aggregated soil surface, and may account for observed longer term effects of conservation farming systems on hydraulic properties of the surface soil.

Table 15. Profile distribution of soil organic carbon, total nitrogen (N) and substrate induced respiration and surface soil water stable macro aggregation after 10 years of a wheat/lupin cropping sequence at Wagga Wagga, NSW.

Soil depth (cm)	Stubble management		Tillage		
	Stubble retained	Stubble burned	Direct drilled	Reduced	Conventional
			Soil organic carbon (t/ha)		
0 - 5	14.66	12.68	16.37	12.53	12.11
5 - 10	14.15	12.86	15.22	13.01	12.28
10 - 15	10.65	9.38	9.47	9.79	10.79
15 - 20	6.67	6.15	6.54	5.96	6.73
LSD 5%	0.88		1.17		
			Total nitrogen (%)		
0 - 5	0.20	0.17	0.22	0.17	0.17
5 - 10	0.17	0.16	0.18	0.16	0.15
10 - 15	0.11	0.11	0.10	0.11	0.12
15 - 20	0.07	0.07	0.07	0.07	0.08
LSD 5%	0.01		0.02		
			Substrate induced respiration (μL CO$_2$/g soil/hr)		
0 - 5	5.5	3.9	5.6	4.5	4.0
5 - 10	1.9	1.6	2.0	1.7	1.5
10 - 15	0.8	0.9	0.7	0.8	1.0
15 - 20	0.8	0.7	0.9	0.6	0.7
LSD 5%	0.9		0.7		
			Water stable aggregation (% wt of aggregates > 250 μm)		
0 - 5	73.8	53.6	74.8	61.9	55.0
LSD 5%	9.2		15.8		

Source: Chan et al. (1992), reprinted with permission[23].

Chan et al. (1992) concluded that farming systems involving cropping mostly reduced SOC in the 0-10 cm soil, but at differing rates depending on soil conservation practice and crop rotational sequencing. In areas where burning and cultivation were practised greater gains were made by modifying tillage practice than from stubble retention, although both practices (DD and stubble retention) assisted in maintaining SOC.

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[23] ©CSIRO Publishing, Collingwood Vic (1992), 2 Oct 2009

2.7 Increased Earthworm Populations

Earthworms are present in soils used for pasture and cereal cropping rotations in south eastern Australia (Baker et al., 1995). The most common species are *Aporrectodea rosea*, which occurred in 45% of sites with an abundance up to 358 earthworms per square metre. Other species include *A. trapazoides*, *Microsclex dubius* and *M. phosphoreus*. These endogeic species burrow continuously in search of food, giving horizontally oriented, frequently extensive and intersecting networks of macropores (Lee and Foster, 1991). Anecic species live in semi-permanent burrows opening to the soil surface and feed at the surface giving vertical channels for water infiltration and gas exchange. Anecic earthworms include *Aporrectodea longa,* although distribution of this species is limited to Tasmania (Chan, 2001).

The claimed benefits of earthworms in cropping systems are improved infiltration of moisture into soil, improved aeration and improved structural stability of the soil (Chan, 2001; Lee and Foster, 1991). At Wagga Wagga, NSW, earthworm populations are related to the frequency of transmitting macropores (r2 = 0.82, Chan and Heenan, 1993). While there was no difference in total macropore number (>1 mm) between tillage treatments, the use of a dye demonstrated that transmitting macropores were more frequent with direct drilling compared with conventional cultivation. The aggregate stability of worm casts was enhanced by orientation of clay and a cement of neutral sugars and polysaccharides excreted by the gut of worms (Shaw and Pawluk, 1986). The casts of enchytraeid worms were also found to be more water stable than bulk soil and to have a stability enhanced by a polysaccharide cement (Chan and Heenan, 1995).

Earthworm populations can respond rapidly to changes in tillage and stubble management. In a tillage and stubble experiment at Harden, NSW, burning stubble in autumn resulted in fewer and smaller adults worms and more juvenile worms in the first spring, although total earthworm numbers (99% *A. trapezoides*) were not affected by stubble burning compared with stubble retention (Doube et al., 1994). Further, where stubble was harrowed with mesh (“bashed”) and left lying on the soil surface, as compared with standing stubble, there were more earthworms (54 vs 34/m^2), more cocoons (94 vs 49 /m^2) and greater biomass (62 vs 50 g/m^2). There was also a strong positive correlation (r = 0.80) between the biomass of earthworms measured in spring and the amount of stubble in contact with the soil surface at the end of the preceding winter.

Similarly, Chan and Heenan (2006) found a doubling in numbers and biomass of earthworms in the second season of a conservation tillage experiment at Temora, NSW. In the no-till treatments in the first season, there were more than 100 earthworms/m^2 where stubble was retained and approximately 30 earthworms/m^2 where stubble was burnt. By the second season, numbers on the retained stubble treatment reached approximately 240 earthworms/m^2, with approximately 100 earthworms/m^2 in the burnt stubble treatment. Where a single cultivation was used prior to sowing, the numbers were 140 earthworms/m^2 for stubble retention and 50 earthworms/m^2 for stubble burnt. Where the treatment was conventional cultivation (3 scarifyings before sowing) earthworm numbers were approximately 45 earthworms/m^2 irrespective of stubble retention. The species was predominantly *A. trapezoides* with a minor component of *M. dubious*.

After 10 years of a lupin/wheat rotation at Wagga Wagga, NSW earthworm numbers in May were not affected by stubble retention, but were reduced by tillage operations (Chan and

Heenan, 1993). Mean numbers were 18 earthworms/m^2 for direct drilling, 11 earthworms/m^2 for a single cultivation before sowing and 4 earthworms/m^2 after conventional cultivation. Both *A. trapezoids* and *M. dubious* were present at the site but were not separated. In the seventh season of a continuous wheat system at Rutherglen, Victoria, Haines and Uren (1990) found no effect on earthworm numbers due to tillage system (cultivated compared with no tillage) when stubble was burnt (mean 120 earthworms/m^2), but with no-tillage, numbers increased from 123 earthworms/m^2 with stubble burning to 275 earthworms/m^2 with stubble retention (standing stubble). Haines and Uren (1990) did not identify earthworms by species in their study, but the site was subsequently reported to have a worm population dominated by *A. rosea* with some *A. trapazoides*, *M. dubius*, *M phosphoreus* and some *Enchytraeidae* (Carter et al., 1994).

Thus, limiting tillage and retaining stubble generally increased earthworm numbers and biomass. It is unlikely that tillage directly damages earthworms. In southern Australia earthworms descend into the soil over summer. Earthworms were found in the surface 10 cm of soil from about June to October (Baker et al., 1993) and were unlikely to be present in the surface soil at the time of cultivation (reduced cultivation in about March with sowing in April/May). The exception was the old fallowing system where cultivation begins in July/August for sowing in the following calendar year. Cultivation may reduce organic matter on the soil surface and damage burrows of earthworms. The observations of Doube et al. (1994), that worm biomass was related to the amount of oaten stubble on the soil surface, suggested that earthworms were feeding on the stubble. Conversely standing stubble had less biomass of earthworms, presumably because the stubble was less accessible to decomposition and earthworm feeding.

Encouraging populations of earthworms may necessitate greater care with use of pesticides particularly insecticides. Earthworm populations were reduced dramatically in the fourth season on a conservation tillage experiment at Temora, NSW (Chan and Heenan, 2006). The population also changed from being dominated by *A. trapezoids* in the first few seasons to be dominated by *M. dubious* by year five. The authors suggested the reduction in population was caused by toxicity of Supracide® (active ingredient methidathion, Edwards and Bohlen, 1996). Other pesticides may adversely affect earthworms. These include the insecticide endosulphan and the nematicide fenamiphos (Choo and Baker, 1998). The herbicides glyphosate and 2, 4-DB and the insecticide/acaricide dimethoate appear to have no affect (Dalby et al., 1995). There remains a need to review pesticide strategy in situations where the establishment or increase in earthworm populations may be considered a benefit flowing from stubble retention.

3. DISADVANTAGES OF STUBBLE RETENTION

Establishment of the subsequent crop has been widely reported as the primary hurdle in stubble-retained systems. This has been viewed as a machinery issue, related to capacity of the sowing machinery to sow through heavy stubble and maintain depth control. However, there were frequent problems with crop emergence and early growth, which have been variously ascribed to allelopathic effects, lower soil temperature under a cover of stubble and shading of the emerging crop. In addition, stubble retention can lead to disease carry over from stubble to the newly sown crop, weed numbers and species can change relative to those seen with stubble burning, effective application of herbicide may be impeded, and nutrients may be immobilised.

3.1 Interference with Machinery

3.1.1 Machinery for stubble

Farmers cited blockages of sowing implements by stubble as the primary reason for non adoption of stubble retention in southern and central NSW (Davis, 2006). Older sowing machinery was limited in its capacity to sow through stubble. In central western NSW about 28% of sowing drills could successful sow through 2 t/ha of stubble at sowing, and only 7% of drills could handle up to 3 t/ha (Vanclay and Hely, 1997).

A single tyne can block with stubble particularly if the straw was wet (Brown et al., 1986). Under the conditions of their experiment, the tyne was capable of moving through a stubble load up to 2.8 t/ha before blocking. However, if the stubble was wet blockages occurred with stubble loads greater than 2.2 t/ha. Dry straw was quite brittle and tended to break and shatter when caught by the tyne. When straw was wet it became less brittle, and there was a tendency for it to bend and wrap around tynes and collect both more straw and soil.

Seeders in stubble-retained systems can give poor crop establishment. This can result from poor soil/seed contact due to the presence of stubble, and from poor depth control. Depth control was compromised by “soil throw” with sowing machinery operated at speed, where soil was displaced from the sowing row giving poor seed cover or was thrown to cover neighbouring rows (Desbiolles and Kleemann, 2003). This excessive soil movement can become a problem if soil incorporated herbicides have been applied. However, in general low plant numbers can be partially compensated for by the crop. For example, Heenan et al. (2000) observed a reduction in the plant density of lupins where stubble was retained (compared with where stubble was burnt), but greater numbers of pods per plant in the stubble-retained systems, suggesting a partial compensation by plants for low initial density.

To facilitate sowing into stubble, many farmers have modified conventional machinery to avoid the cost of purchasing specialized machinery. This was particularly so in the initial stages of adoption of stubble retention. Modifications include those to the tyne itself; increasing the height of the tyne and changing the shape of the tyne from rectangular to more circular to shed stubble more readily. Tyne arrangement on the implement can also be changed by increasing the length between rows of tynes, and increasing the spacing of tynes within the row (Mead and Qaisrani, 2003). However, even these modified tyned implements could not handle 3.2 t/ha of standing stubble and required that stubble be either harrowed or flailed. Straw lengths of 200 mm or less (60% of stubble) used in combination with the above machinery modifications enabled machinery to operate without major blockages, up to the 4.7 t/ha of stubble (the maximum tested, Mead and Qaisrani, 2003). This strategy would be sufficient to handle most stubble loads in Australia.

Some of the problems associated with sowing were able to be overcome if farmers were prepared to purchase new machinery or undertake extensive modifications. Disc seeders were less likely to block in stubble than tyned implements. Coulters can cut stubble, though not always successfully. There were also fingered wheels which sweep stubble from in front of the sowing tyne or disc (Green, 1997) or rubber fingered wheels can be used to "walk down" the stubble preventing stubble from building up on the soil opener (Siemens et al., 2004). Recent innovations such as "StubbleStar®" (Gregor et al., 2007) and the "Happy Seeder®" (Sidhu et al., 2007) have the ability to sow into heavy stubbles (12 t/ha and 9 t/ha, respectively).

3.1.2 Decomposition of stubble

Stubble decomposition in the 4 to 6 months from harvest to re-sowing was a primary influence on the amount of stubble remaining at sowing. Amato et al. (1987) examined the decomposition of wheat straw incorporated into the soil at 12 locations in southern Australia over 2 years (Figure 19). Approximately 70% of the stubble remained by the time of sowing in the following season (after about 5 months).

By contrast a study at Toowoomba, Queensland showed a more rapid reduction in the quantity of incorporated wheat stubble with about 36% remaining in the soil after 5 months (Cogle et al., 1987). Such a difference would suggest that retaining stubble in the subtropics, with summer dominant rainfall, presented fewer problems when re-sowing the following crop than in southern Australia where rainfall was either weakly or strongly winter dominant and dry summers were common. However, Cogle et al. (1987) included a treatment with straw retained on the soil surface and observed slightly slower decomposition compared with incorporated straw (Figure 19), about 7% more straw was present by sowing. This was presumably due to the poorer contact of surface retained straw with soil. In practice, stubble was frequently left standing and may be slower to break down than stubble lying on the soil surface.

While Australian data on the breakdown of stubble in contact with the soil surface was limited, overseas data indicated that standing and surface-contact stubbles decompose more slowly than incorporated stubbles (Figure 20). However, the surface-applied stubble treatment in Cogle et al. (1987) appeared to decompose more rapidly than similar treatments at all the USA sites, but comparably to the UK site. In addition to placement, decomposition of stubble was influenced by stubble composition (Douglas et al., 1980) and by climate - both moisture and temperature. These effects have been modelled and validated against field data in the USA (Douglas and Rickman, 1992; Stroo et al., 1989).

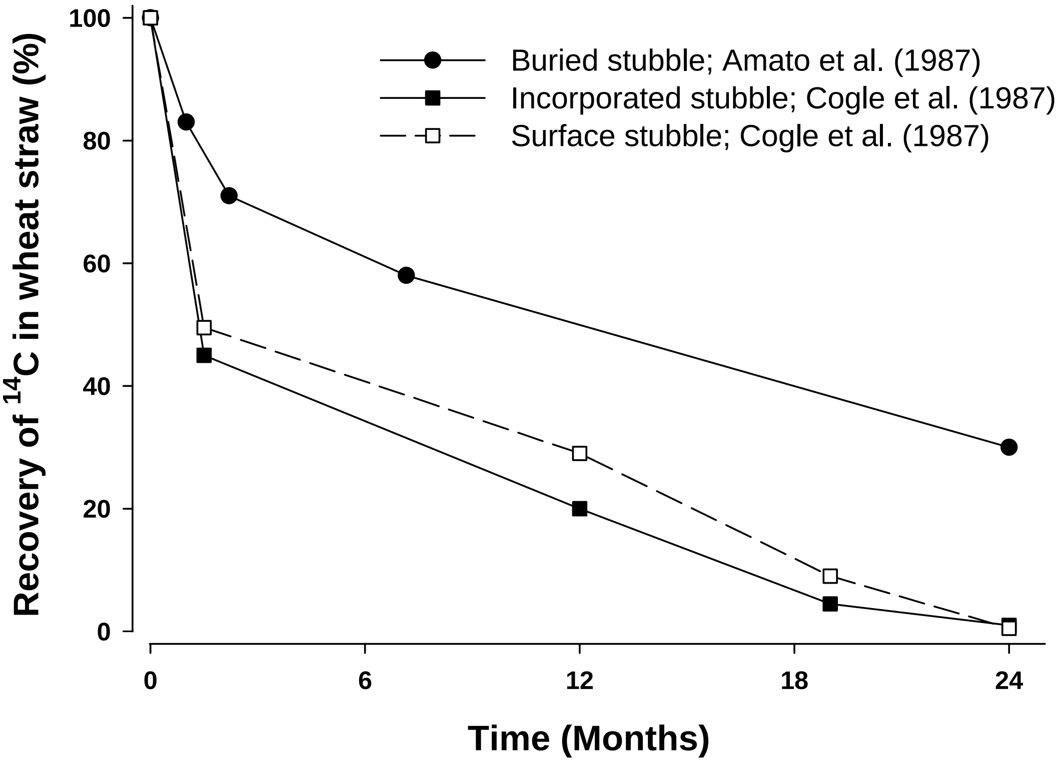

Figure 19. The recovery (%) of ^{14}C from straw applied to the soil surface or incorporated into soil at one site in south east Queensland (Cogle et al., 1987) or from straw incorporated into soil at 13 field sites in southern Australia (Amato et al, 1987). Source: Cogle et al. (1987) and Amato et al. (1987), reprinted with permission[24].

Examples from the literature give an indication of the range of decomposition rates of wheaten stubble in the field in Australia (Table 16). In addition to the work of Cogle et al. (1987) in Queensalnd, where 43% of surface applied stubble and 36% of incorporated stubble remained at sowing, Wang and Dalal (2006) reported greater rates of stubble breakdown, with only 16% of stubble remaining irrespective of whether it was incorporated or left standing. Again, summer dominant rainfall and warm conditions over summer/early autumn in northern areas appear to give rapid breakdown of stubble between post harvest and sowing the following autumn.

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[24] ©CSIRO Publishing, Collingwood Vic (1987), 2 Oct 2009

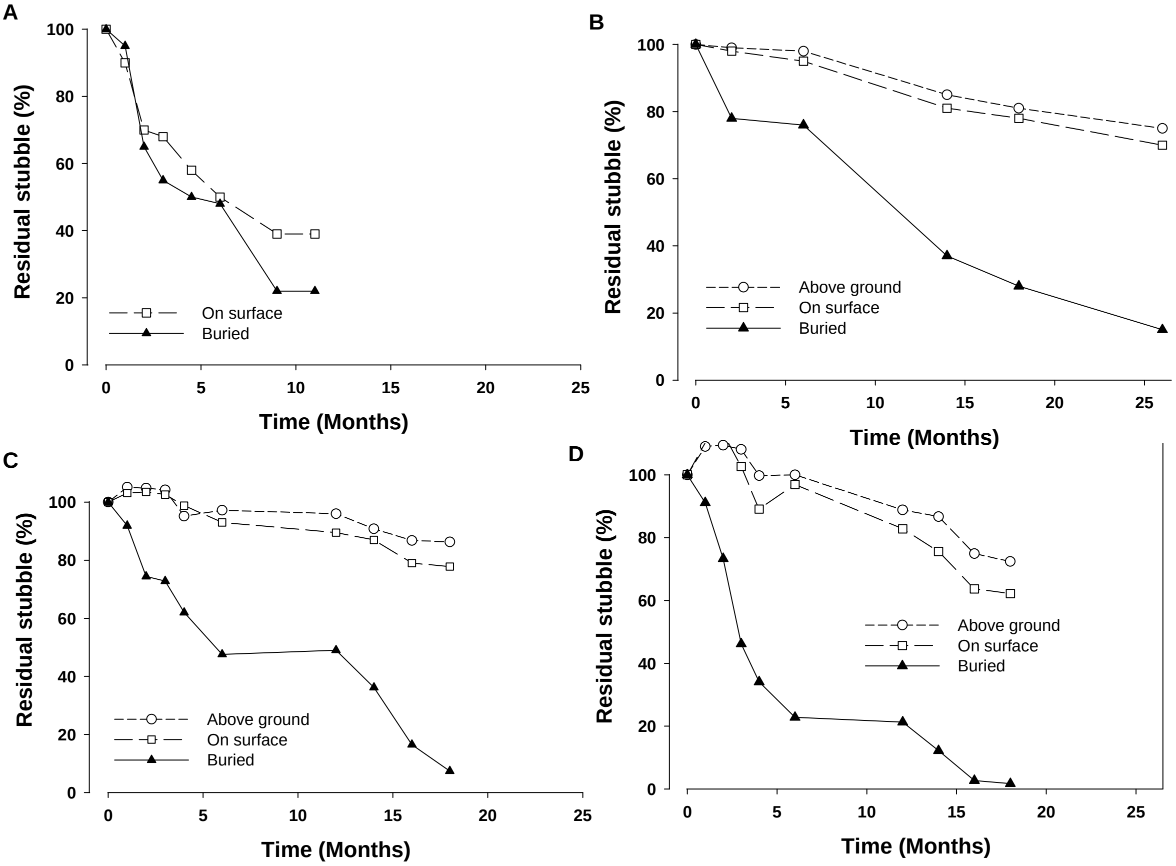

Figure 20. Loss of residue weight (% of initial) with time for stubble in the field placed either above ground, on the soil surface or buried, to simulate standing stubble, mulched stubble and incorporated stubble respectively, for (A) oaten stubble at 4444 kg/ha in the UK, Adapted from: Harper and Lynch (1981), (B) wheaten stubble at 4300 kg/ha in Pendleton Oregon, Source: Douglas et al. (1980), reprinted with permission[25], (C) wheaten stubble at 4484 kg/ha at Bozeman Montana, Adapted from: Brown and Dickey (1970), or (D) wheat stubble at 4932 kg/ha at Huntley, Montana, Adapted from: Brown and Dickey (1970).

Losses from undisturbed stubble between harvest and sowing in NSW ranged from 25% to 35 % (i.e. 65-75% of stubble remaining, Table 16). Where stubble was grazed by sheep, 66-72% of stubble remained at sowing (Mulholland et al., 1976b). In WA the average amount of stubble remaining in 1997-98 ranged from 43-62%, although the management operations on these stubbles were not defined (Bhathal and Loughman, 2001). In the 1998/99 season the percentage of remaining stubble (71-91%) was more typical of the figures for other areas of the southern cropping zone.

Operations such as incorporation, “bashing” or “mulching” decreased the stubble remaining at sowing, although burning was the most effective stubble removal operation (Doube et al., 1994). “Bashing” involved harrowing with steel mesh, while “mulching” was done using a flail mulcher which cut stubble into 5-10 cm lengths. These operations increased the stubble/soil contact and accelerated stubble decomposition.

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[25] ©Soil Science Society of America (1980), 2 Sept 2009

Table 16. The reduction in weight of wheaten stubble between harvest and sowing in the field with different treatments and in various Australian regions.

Stubble weight (t/ha)			Stubble remaining (%)	Stubble treatment	Comment (Reference)
Post harvest	Pre sowing	Loss by sowing			
			Queensland		
4.6 t/ha^1	0.76 t/ha^1	3.9 t/ha^1	**16.3%**	Incorporated	Single experiment (Wang and Dalal, 2006)
5.3 t/ha^1	0.84 t/ha^1	4.4 t/ha^1	**16.0%**	standing (no-till)	
na	na	na	**36%**	Incorporated	Single experiment (Cogle et al., 1987)
na	na	na	**43%**	Surface applied	
			Northern NSW		
3.2 t/ha^2	2.44 t/ha	0.80 t/ha	**75%**	Retained	Mean over 3 seasons (Burgess et al., 1993)
3.4 t/ha^2	1.62 t/ha	1.80 t/ha	**47%**	Incorporated	
4.0 t/ha^2	0.37 t/ha	3.60 t/ha	**9%**	burnt	
			Southern NSW		
3.9 t/ha	2.52 t/ha	1.38 t/ha	**65%**	Standing	Feb 8 to Aug 17, 1990 (Doube et al., 1994)
3.9 t/ha	2.09 t/ha	1.81 t/ha	**54%**	"bashed"	
3.9 t/ha	1.36 t/ha	2.54 t/ha	**35%**	"mulched"	
3.9 t/ha	0.32 t/ha	3.58 t/ha	**8%**	burnt	
3.0 t/ha	2.15 t/ha	0.85 t/ha	**72%**	Grazed 13 sheep/ha	Exp 1, 1970 (Mulholland et al., 1976b)
4.3 t/ha	2.9 t/ha	1.4 t/ha	**66%**	Grazed 15 sheep/ha	Exp 2, 1971 (Mulholland et al., 1976b)
5.5 t/ha	3.75 t/ha	1.75 t/ha	**68%**	Grazed 15 sheep/ha	Exp 3, 1972 (Mulholland et al., 1976b)
			Victoria		
2.0 t/ha	1.7 t/ha	0.31 t/ha	**85%**	Ungrazed	One site (Robertson, 2002)
			Western Australia		
5.6 t/ha (range 4.1-6.4 t/ha)	2.9 t/ha (range 1.8-3.8 t/ha)	2.7 t/ha (range 2.3-3.0 t/ha)	**51%** (range 43%-62%)	Farmer managed stubble retention	Mean of 7 sites 1997/98 season (Bhathal and Loughman, 2001)
4.8 t/ha (range 4.0-6.6 t/ha)	3.8 t/ha (range 3.1-4.6 t/ha)	1.0 t/ha (range 0.5-1.9 t/ha)	**80%** (range 71%-91%)	Farmer managed stubble retention	Mean of 10 sites 1998/99 season (Bhathal and Loughman, 2001)

[1] assumed stubble was 45% carbon.

[2] estimated from grain yield and Perry (1992).

3.1.3 Stubble pre-treatment

Stubble management at harvest and over summer can help to overcome some of the sowing problems encountered in stubble-retained systems. A low cutting height at harvest (30 cm) can assist subsequent sowing operations, and straw spreaders distribute straw more evenly preventing a build up of larger quantities of stubble in the harvester windrow. Stubble treatment through mulchers or slashers was also a possibility. Working with heavy stubble loads (9.8 and 10.5 t/ha) in Oregon, USA, Siemens and Wilkins (2006) studied sowing, early crop density and growth from applying a range of stubble pre-treatments. They concluded that sowing into heavy stubbles generally required a standing stubble height less than or equal to the row spacing (30 cm in their experiments) and that the majority of cut stubble was less than 18 cm in length. These requirements were achieved by use of a straw chopper and chaff spreader and stubble height was controlled by the height of the header cut or by a subsequent flail operation. Using an additional low cutter bar at harvest to cut the stubble to 20 cm was less successful, and the authors suggest that the cut straw in this system retained its structural integrity, while straw cutters or flails shattered the straw. However, in the Australian setting there would be an added fire risk if operations in stubble (such as slashing) were carried out over summer.

These machinery operations have a cost which must be offset by any advantages of stubble retention. The operations identified above may be necessary in order to retain surface stubble in a direct drill or no-till system. They can be considered separately from the costs/benefits of the tillage system. The move to direct drilling crops with stubble burning reduced cultivation operations, but increased the cost of herbicides and their application. These changes were economically justified (Godyn and Brennan, 1984). The subsequent adoption of stubble retention requires sowing machinery modification or replacement, potentially cutter bar and a straw spreader addition to the harvester, and possibly additional field operations of stubble harrowing, flailing or slashing.

However, for a farmer the presence of a large amount of stubble represented a risk. The risk was that sowing of the following crop could be either slow or not possible with the machinery available. When sowing operations continued through the night, straw would be damper and sowing equipment more prone to blockages. Farmers will not tolerate frequent blockages when they are trying to sow large areas of crop as quickly as possible for timely establishment of crops. Hence the burning of crop residues remained a dominant practice in south-eastern Australia.

3.1.4 Row spacing and retained stubble

In order to cope with high stubble loads, an increase in row spacing may improve sowing operations by improving trash flow through sowing machinery and reducing the risk of blockage. There was an additional advantage in that tractor draft was reduced. However the widening of rows from the standard 18 cm may be associated with yield loss (Figure 21).

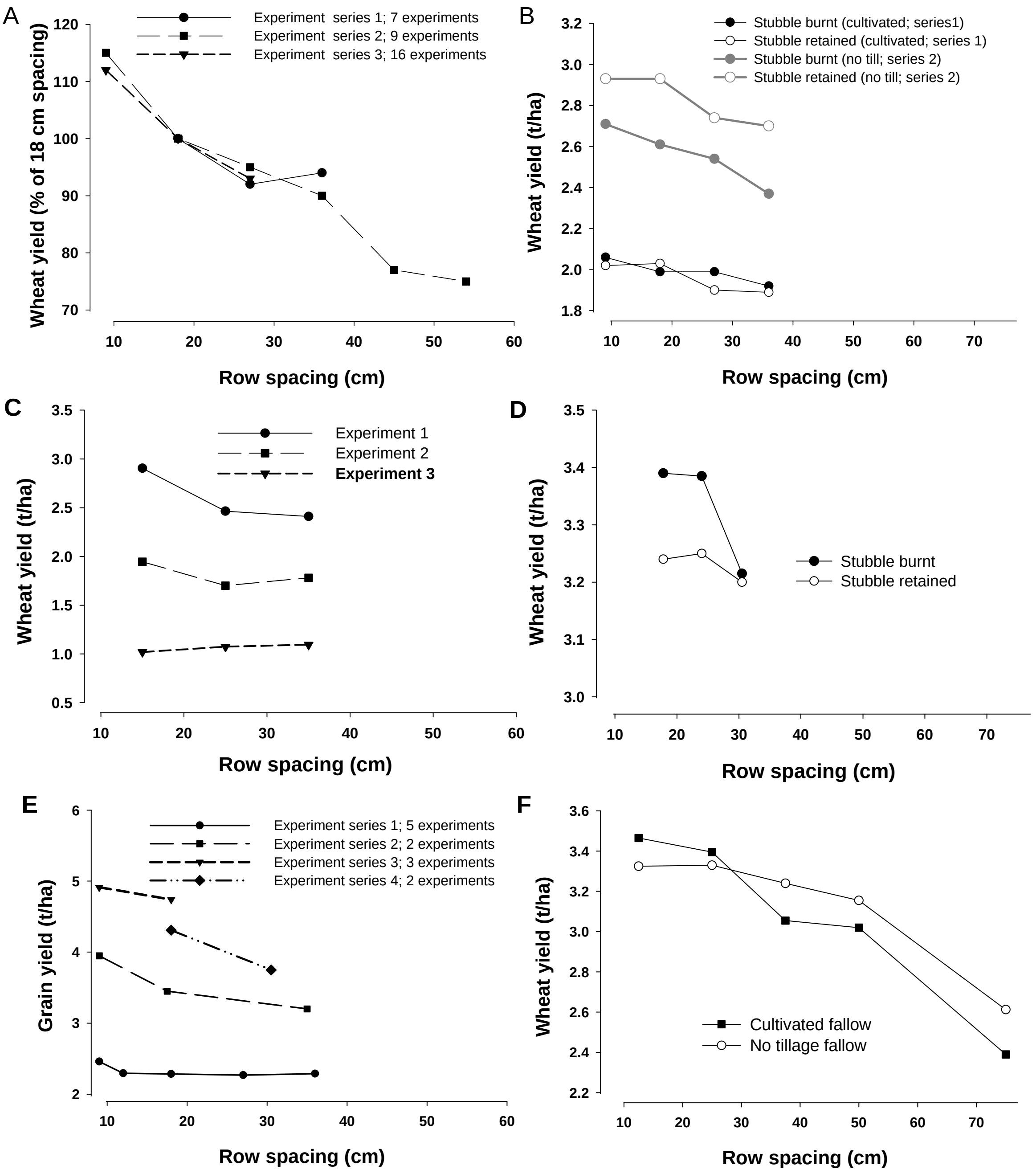

Figure 21. Relationships between row spacing in wheat and grain yield in WA (a) Reithmuller cited by Anderson et al. (2000) and (b) Reithmuller (2004), central NSW (c) and (d) Fettell and Bamforth (1986) and in either South Australia (e) Smith et al. (1995) or northern NSW (f) Doyle and Felton (1984). Row spacing effects were studied with no stubble present (a, c and e), or by comparison between stubble on the soil surface and stubble burnt (b and d) or stubble incorporated (f).

Averaged over 32 experiments sown into bare soil in WA, yield was reduced by about 1% for every centimetre widening of row space (Figure 21a, Reithmuller cited by Anderson et al., 2000). It follows that widening row spacing from 18 cm to 25 cm would reduce yield by 7%. In SA (Figure 21e), Smith et al. (1995) summarised data on the effect of widening rows of wheat and concluded that yield was reduced by an average of 4.3% when rows were widened from 18 cm to 30-36 cm. In central west NSW, yield was reduced in one experiment (Experiment 1, Figure 21c), but not in two other experiments where final yield was lower. This trend for wider row spacing to have a smaller effect on yield when yield potential was low was also supported in the SA data (Figure 21e).

Some experiments have compared widening row space in the presence and absence of stubble; presumably because of an anticipated interaction. Yield of grain showed similar declines with increasing row spacing, irrespective of stubble management when averaged over five seasons in both series of experiments in WA (Figure 21b, Riethmuller, 2004). Stubble retention reduced yield slightly compared with stubble burning where soil was cultivated (series 1, between 1988 to 1994), but increased yield with no-tillage (series 2, 1995 to 2003). An interaction may be present in data from a single experiment in northern NSW (Figure 21f, Doyle and Felton, 1984). Here, the cultivated fallow would have buried a large amount of the stubble while, it was presumed, the no-tillage fallow would have carried a standing stubble from a previous crop. The effect on wheat yield of widening the sowing rows was slightly less where stubble was retained. At narrower row spacing (18 and 25 cm), retaining stubble reduced yield compared with incorporating stubble, but with row spacing wider than 25 cm, yield was reduced in both systems, though less so with retained stubble. A trend to this same interaction was contained in data from central NSW (Figure 21d, Fettell and Bamforth, 1986). Data have been averaged over two experiments, both using direct drilling. At row spacings of 18 and 24 cm, yields were higher where stubble was burnt rather than retained, and at 31 cm there was no apparent difference in yield between stubble management treatments.

In the above experiments in northern NSW (Figure 21f, Doyle and Felton, 1984) and central NSW (Figure 21d, Fettell and Bamforth, 1986) it was apparent that with conventional row spacing (18 to 25 cm) stubble retention lowered yields of wheat compared with stubble burning or incorporation, consistent with data presented later in the current review. In the WA data (Figure 21b) slight yield reduction due to stubble retention occurred in the cultivated series of experiments, but stubble retention increased yield with no-till in an independent series of experiments. It appeared that retaining stubble, if it has any effect, may reduce the rate of yield loss with row spacing widths of 36 cm and wider.

As in the absence of retained stubble, water evaporation from soil had been shown to be greater in crops grown under wider row spacings (Eberbach and Pala, 2005). A positive effect of stubble mulch may be to slow evaporation during the early growing season (before canopy closure) and improve water availability to crops at wider rows. The end result may be a greater proportion of available water was transpired by crops established at wide rows into stubble, compared with no stubble. At wider rows, and without stubble, greater between row drying of soil may also reduce access to nutrients in that zone. Alternatively, in a narrow row setting, the presence of stubble may have some hitherto undefined adverse effect on yield that was reduced by widening of row width.

Over 5 sites in WA Paynter and Hill (2007) found barley sown in wide rows (36-50cm) produced 3.2 t/ha compared with 3.5t/ha achieved when sown in narrow rows (18-25 cm). However this was not consistent across sites with significantly lower yield, due to wide rows sowing, at 3 of the 5 sites. Barley and wheat appeared similar in that wide row sowing may lower grain yield, but that this was not always the case particularly in low yielding situations.

The advantages of wide row sowing of cereals for stubble handling led to suggested alterations to seed distribution in the row. Amjad and Anderson (2006) altered the within row seed arrangement and compared a narrow band (25 mm) dispersal of seed in the sowing "ribbon", typical of a disc or narrow point tyne, with a wider within row seed dispersal (50 and 75 mm). At 360 mm row spacings wheat yield was increased by the wider within row seed dispersal. This simple change in sowing pattern, which can be achieved with some machinery modification, was a partial step to the twin or paired row sowing arrangement. In this system a fertiliser row was central and sown deeper than two seed rows which were displaced laterally to each side of the fertiliser band. This arrangement gave seed/fertiliser separation with each seed row still having early access to the fertiliser band, while simultaneously arranging plants to give more rapid canopy closure from wide row spacings. Yield improvements in wheat have been recorded for paired row sowing compared with single row sowing at row spacings of 25, 38 and 51 cm (Xie et al., 1998). However capital expenditure was required by the farmer for new machinery.

Studies with the widening of rows with lupins show that, in WA in 1990 and 1991 over 23 experiments, there was a small positive yield increase, of 3.6% or 48 kg/ha of grain from wider rows (36-38 cm) compared with narrow rows (18-19 cm, Jarvis, 1992a; Jarvis, 1992b). Little was reported on row spacing for canola. In Canada, Xie et al. (1998) found that yield from a 38 cm row spacing was not different from 25 cm row spacing in one season, and gave higher yield in another season. Paired row sowing gave higher yield than single row sowing. However the broad leaf crops appear to be less sensitive to yield loss with widening row spacing than cereal crops and may benefit from wider rows in some situations.

In summary, widening of row spacing to improve stubble flow through machinery appeared likely to reduce grain yield of cereals, in all except low yielding situations. The role of retained stubble in modifying this effect was unclear. However, broadleaf crops appeared to suffer no yield loss, or even had slight yield gains by widening row spacing beyond 18 cm. Paired row sowing offered improved stubble flow through machinery while enabling earlier canopy closure compared with single row sowing. This should reduce the yield loss associated with wider row spacing of cereals.

3.2 Animal Production and Stubble Retention

In most seasons, sheep graze stubbles in southern Australia. This is not practised in the North American cereal belt where stubble retention was pioneered (Poole, 1987), nor in the northern areas of the Australian grain growing region. Grazing of stubbles was claimed to cause soil compaction (Packer et al., 1985) and trampling and tangling of stubble, causing machinery blockages at sowing.

The quality of wheaten stubble for animal production was low and declined with weathering over the summer and autumn (Robertson, 2002). In north-western Victoria, in a wetter-than-normal season, quality of ungrazed wheaten stubble straw declined from dry matter digestibility of 41.8% in December to 33.6% in late May, while leaf biomass also declined (49.7 to 37.7%) in the same time period (Robertson, 2002). Sheep consumed little cereal stubble, but retrieved grain and graze leaf and volunteer weeds and self-sown crop.

Sheep sought out green feed in the stubble, with their diet consisting of 80% green feed when as little as 40 kg/ha of dry matter was available as green feed (Mulholland et al., 1976b). Little stubble was consumed, only 1.6 and 11.9 kg/ha (14% and 36% of the total disappearance of crop residue) at 15 and 30 sheep/ha, respectively. Mulholland et al. (1976a) suggested that cereal stubbles with some green material gave a source of grazing at stocking rates up to 30/ha for about 12 weeks.

Mulholland et al. (1976a) also compared grazing in stubbles of pea and lupin and oat. The straw of each type was of uniformly low digestibility (30%), but legume straw was consistently higher in N than oaten straw (1.4 vs. 0.77 per cent N). However, regardless of straw type, most of the crop residue remained at the end of the experiment because the sheep showed a strong preference for green material. There was a small liveweight gain at the 11.25 sheep/ha and a weight loss at 22.5 sheep/ha. Sheep grazing pea stubble at 11.25 sheep/ha gained 3 kg more than those on oats, but the difference was not statistically significant.

Grazing of stubbles (or more precisely leaf, spilt grain and weeds) can be an important contributor to the animal production enterprise (Robertson, 2006), and may save on herbicide costs for weed control. The grazing enterprise would in this case partially complement a cropping enterprise. However, in drought seasons farmers may graze the crop in spring in an attempt to recover some value from the cropping enterprise and compensate for poor pasture growth. An alternative is to cut the crop for hay. Both grazing and hay cutting were driven by the need to maintain the parallel grazing enterprise on the mixed farm and may result in little stubble being available to protect soil from wind or water erosion or to promote moisture infiltration. In the drought years of 1982, 1994 and 2002 the central and southern wheat belt of NSW was subject to some wind erosion and dust storms. However, the management of sheep and cattle in drought seasons was a problem in both stubble-burnt and stubble-retained systems.

Grazing of stubbles in southern cropping areas was an important source of feed and may minimise the need for spraying for weed control. However, grazing may present other limitations in systems of stubble retention.

3.3 Disease Carry Over in Stubble-Retained Systems

Burning stubble reduces the disease potential for a subsequent sensitive crop. However, the temperatures achieved in a stubble fire may influence the effectiveness of the fire in controlling some plant disease carrying over on the stubble.

3.3.1 Temperature of field burns

Hind-Lanoiselet et al. (2005) studied the effects of fire in wheat and rice stubble burns in the field on the survival of *Sclerotinia sclerotiorum* removed from canola. The temperatures were recorded using melting crayons placed in open petrie dishes in the stubble. The maximum temperature in the burn varied with position in the stubble; temperatures on fallen stubble were in the range 121-177°C (63% of dishes in this range), as compared with less than 93°C under fallen stubble (82% of dishes) and among standing stubble (93% of dishes). Approximately 90% ground cover of stubble was required to reduce survival of sclerotia in a wheat stubble burn producing temperatures of 93 to 121°C. The highest temperature recorded at a location was 218°C (Hind-Lanoiselet et al., 2005). The authors concluded that stubble burning may be ineffective as a control strategy for *Sclerotinia*, as temperatures of 121°C were not reached at most locations within the stubble.

In western Canada field stubble burning produced temperatures up to 338-422°C at the soil surface within two minutes of fire initiation (Biederbeck et al., 1980) and maximum air temperatures of 301, 416 and 315°C were recorded within 25, 75 and 250 mm of the soil surface within 30 seconds of fire initiation in the Pacific Northwest of the USA (Rasmussen et al., 1986). In both these situations the soil below either 1 cm (Biederbeck et al., 1980) or 2.5 cm (Rasmussen et al., 1986) was almost unaffected by the burn and temperature reduced rapidly at the soil surface (Biederbeck et al., 1980) or in the air (Rasmussen et al., 1986). Wilson and Cussans (1975) reported an average maximum temperature at the soil surface of 500°C, with 200°C maintained for 1-2 minutes. The temperatures achieved in a burn would be expected to be critical in drawing conclusions about the effectiveness of stubble burning in controlling crop diseases borne on stubble. However, some measure of disease control as a result of stubble burning has been reported in the field.

3.3.2 Disease carry over

A change of practice from stubble burning to retention of stubbles may significantly increase diseases, particularly those diseases that survive in stubble. In the Australian wheat cropping areas, increases in disease have been noted for crown rot (*Fusarium pseudograminearum, F. culmorum*), common root rot (*Cochliobolus sativus (syn Bipolaris sorokiniana)*), yellow spot (*Pyrenophora trtici-repentis*), eyespot (*Oculimacula yallundae* (syn *Tapesia yallundae*, *Pseudocercosporella herpotrichoides*)) and take-all (*Gaeumannomyces gramininis* var *tritici*) associated with stubble retention. With a need to maintain stubble retention for reasons associated with soil benefits, interest has turned to control strategies for these diseases. The main strategies were through chemical control, bio-control, disease resistance in crops and cultural practices, particularly crop sequencing options (Bockus, 1998).

Crown rot

Crown rot occurs throughout the cropping areas of Australia and is a particularly important disease in Queensland and northern NSW (Backhouse et al., 2004; Murray and Brown, 1987). A number of studies have shown that burning soon after harvest reduced the incidence of crown rot both in Queensland (Dodman and Wildermuth, 1989; Wildermuth et al., 1997) and northern NSW (Klein et al., 1988; Summerell et al., 1989). However, a late burn (prior to sowing in the following year) appeared to be less effective than burning soon after harvest (Klein et al., 1988). Additionally, burning was never a completely effective control measure. Early burning at Moree (northern NSW) gave partial control (Burgess et al., 1993), with the burn giving a lower incidence of infection in 2 of 5 years at one site, and in 3 of 4 years at another site. This ineffectiveness was ascribed to incomplete burning and the presence of susceptible weed hosts. In subsequent experiments, late burning with continuous wheat gave more reliable control compared with stubble retention; late burning maintained crown rot incidence below 10% over 4 seasons while with stubble retention it was 35% in the final two seasons.

Burial of stubble has reduced survival of crown rot and was associated with stubble breakdown (Summerell and Burgess, 1988). However, incorporation of stubble has been ineffective in reducing the incidence of crown rot as compared with retention of stubble residues on the surface of the soil (Summerell et al., 1989). The incidence of disease was similar in plots whether stubble was retained on the soil surface or incorporated (Burgess et al., 1993). The completeness of stubble incorporation and the effect of this on stubble decomposition may be important in determining effectiveness for control of crown rot.

Crop sequencing has given some control of crown rot. Burgess et al. (1996) used a wheat/sorghum system and found crown rot infection of about 15 % compared with a continuous wheat system where the incidence of the disease was 30 to 65% (incidence depended on season). Oats and barley have been investigated as “break” crops (Nelson and Burgess, 1995). Both cereals were infected, but oats did not express symptoms in some seasons. One and two season “break” crops of barley and oats did not reduce crown rot incidence significantly in a following wheat crop (final incidence 81%), although continuous wheat had highest infection and mown oats the lowest. Backhouse (2006) predicted crown rot infection, based on incidence in the previous season, summer rainfall and either yield or in-crop rainfall in the previous season. These multiple regressions accounted for 65–81% of the variation in disease incidence in the target crop in northern NSW (Moree), and 86% of the variation in incidence in Queensland (Billa Billa). Backhouse suggested that a predicted high incidence could be managed by using resistant cultivars, sowing a break crop or burning the stubble.

Differences in crown rot susceptibility of cultivars have been observed in the field (Purss, 1966; Wildermuth and Purss, 1971). This partial resistance has been associated with the varietal differences in depth of the crown (Wildermuth et al., 2001). As the primary site of infection was the stem base and leaf sheath, a shallow crown depth was believed to minimise the chance of infection. This suggested an agronomic issue (shallow sowing gives shallower crown depth) and a breeding approach may be optimal.

The cultivars Sunco and Pelsart did not behave in accordance with this trend, suggesting a different source of partial resistance. More recently a range of germplasm sources of partial resistance have been reported, with genetic markers identified, in *cv* Kukri (Wallwork et al., 2004), line W21MMT70 (Bovill et al., 2006) and line 2-49 (Collard et al., 2005; Collard et al., 2006). This sustained interest in breeding for resistance was a result of the practice of stubble retention being current practice in Queensland and northern NSW. More recently the practice of sowing a new crop with wide row spacings (360 mm) between the wide stubble rows of the previous crop was shown to minimise infection by crown rot of the new sown crop (S. Simpfendorfer pers comm.)

Common root rot

Common root rot is a less important disease than crown rot, although it occurs throughout the Australian wheat belt (Murray and Brown, 1987). It is associated with stubble in Brazil, but when the wheat stubble decomposed over 20 months there was an absence of fungal conidia at 17 months suggesting nutritional dependence of the fungus on the stubble substrate (Reis et al., 1998). Common root rot was of lower severity when stubble was removed as compared with stubble-retained treatments (Wildermuth et al., 1997). When compared with any of the other tillage treatments no-tillage resulted in lower disease severity in Queensland (Wildermuth et al., 1997) and lower incidence in Victoria (de Boer and Kollmorgen, 1988).

The long association of the fungus with stubble suggests crop rotation as an approach to control. Additionally, wild crosses have transferred a source of resistance from *Thinopyrum ponticum* into wheat (Li et al., 2004b).

Eyespot

Eyespot is an important disease in southern NSW and Victoria, with a low incidence in SA; the disease has not been recorded in WA, Queensland or northern NSW (Murray and Brown, 1987). In north-eastern Victoria the incidence of eyespot increased under stubble-retention compared with stubble-burnt systems (de Boer and Kollmorgen, 1988). In continuously cropped wheat with direct drilling and stubble retention the disease incidence was 3, 46 and 66% (in 1984, 1985 and 1986) compared with 4, 19 and 33% where stubble was burnt. Cultivating the soil after burning increased the incidence of eyespot. In southern NSW eyespot was also associated with stubble retention (Murray et al., 1991). In a direct drilled wheat/lupin rotation eyespot incidence on tillers of wheat was 35.5% for stubble-retained, compared with 7% for stubble-burnt systems in the wet season of 1983. In addition, where stubble was retained, eyespot was at a higher incidence in cultivated (75%) rather than direct drilled plots (35%). In 1983 and 1984 eyespot incidence on tillers was related to loss in grain yield.

Chemical treatment of eyespot has been pursued, but resistance to some chemicals has appeared. This has increased interest in a genetic solution for eyespot control. Resistance to eyespot has been introgressed from *Triticum ventricosm* (Doussinault et al., 1983), *Dasypyrum villosum* (Yildirim et al., 2000), and *Thinopyrum ponticum* (Li et al., 2004a, 2005). *Pch-1* (from *Triticum ventricosm*) has been used extensively in the US Pacific Northwest but may have caused a change in the species of causal organism of eyespot from predominately *Oculimacula yallundae* (syn *Tapesia yallundae*, *Pseudocercosporella herpotrichoides*) to greater proportions of *Oculimacula acuformis* (syn Tapesia acuformis, Pseudocercosporella herpotrichoides var acuformis, Li et al. 2005). This has renewed interest in chemical treatments for *Oculimacula acuformis* (Ray et al., 2004).

Yellow spot

Yellow spot occurred in all major areas of cereal cropping in Australia and is an important disease (Murray and Brown, 1987). It is generally considered that stubble retention has contributed to increasing incidence of the disease in Victoria and NSW (Clarke and Gagen, 1988; Wong, 1977). Murray and Brown (1987) suggested the greater incidence in the Queensland and northern NSW was due to increased adoption of stubble retention.

Stubble burning was an effective control of yellow spot where a crop sown after 5 season of stubble burning had 0.8 lesions/leaf, compared with 2.4 lesions where stubble was incorporated and 11.8 lesions where stubble was retained and untreated (Rees and Platz, 1979). These authors suggest stubble burning or incorporation as control strategies in Queensland. Similar results were obtained in northern NSW after a single season of applying the same stubble management strategies (Summerell et al., 1988). However, viable yellow spot was recovered infrequently from naturally infected stubble buried in nylon mesh bags after 26 weeks and, where stubble was incorporated by rotary hoe, viable yellow spot was reduced after 52 weeks (Summerell and Burgess, 1989). Recovery of the fungus from surface retained stubble was reduced by 50% after 104 weeks, suggesting that surface retained stubble, which was slower to decompose, was a more persistent source of infection for following crops. In north-east Victoria, stubble burning prior to sowing reduced the incidence of yellow spot in direct drilled wheat by 50 to 85%, depending on season (de Boer and

Kollmorgen, 1988). Stubble incorporation prior to sowing was also an effective control measure and de Boer and Kollmorgen (1988) regarded the disease of low incidence in north-eastern Victoria and restricted to immature crops.

The effect of crop rotation in disease infectivity by yellow spot has been investigated in WA (Bhathal and Loughman, 2001). In a wheat/lupin/wheat rotation the authors examined the carryover of infectivity of stubble from the first wheat crop into the second wheat crop. Stubble retained from the first crop of wheat was reduced to 1-8% when the second crop was sown about 18 month later. At this time the stubble induced significant disease in 6 of 44 (14%) cases examined. The authors did not distinguish leaf lesions due to yellow spot from those due to *Septoria nodorum* blotch. However, while they considered the break crop of lupins to be sufficient to significantly reduce disease risk to the second wheat crop, a significant risk remained suggesting that management of disease carry over on stubble of the crop from two years earlier, rather than just one year, may need to be considered. This may involve two non-host crops between wheat crops.

Varieties are known to vary in their reaction 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).

Take-all

Take-all is an important disease in all areas of the Australian wheat belt, although it is of lesser importance in Queensland (Murray and Brown, 1987). However, the role of stubble retention in the incidence of take-all is unclear.

At a site in the northern Wimmera of Victoria, the application of a clean stubble mulch over infected crowns reduced survival of take-all in the crowns from 49% with no mulch, to 29% with 4 t/ha of stubble (Kollmorgen et al., 1987). Burial of the crowns at 5 or 10 cm also reduced survival of take-all. At Rutherglen and Wilby (north-eastern Victoria), stubble was either retained standing, retained after flail mulching, burnt or incorporated prior to sowing (de Boer et al., 1992). At the Rutherglen site, with low take-all incidence, stubble management had no effect on incidence or severity of take-all. At the second site (Wilby) at early tillering, the incidence and severity of take-all was higher where wheat stubble had been incorporated into the soil (16% plants affected), compared with where stubble was left standing, mulched or burnt (2, 3 and 4%, respectively). At anthesis the treatments did not differ and incidence averaged 81 % of plants affected. Again in a long-term experiment at Rutherglen, stubble retention compared with stubble burning did not significantly influence take-all incidence or frequency over three seasons, whether the crop sequence was continuous wheat or wheat/lupin, although incidence and severity were lower in the wheat/lupin system (de Boer et al., 1993).

At Wagga Wagga, NSW, take-all incidence in a wheat/lupin/wheat rotation was associated with stubble retention (Murray et al., 1991). In 1983, where the wheat was direct drilled and stubble retained 22% of tillers showed symptoms, compared with stubble burning with 1% of tillers affected. These authors suggested that infected stubble from wheat in the 1981 season did not decompose in the lupin crop during 1982 due to drought, and was carried into the 1983 season to infect the 1983 wheat crop.

Suppression of take-all fungus had been observed particularly where continuous wheat crops were sown. Suppression of take-all infection was observed in soil from two long-term sites in central/southern NSW (Cowra and Harden) using inoculated soil in pots in a seedling bioassay (Pankhurst et al., 2002). Suppression was ascribed to the greater organic carbon and microbial biomass in the conservation farming treatments, but the treatments tested did not permit stubble retention practices to be separated from tillage practices, as conventional cultivation and stubble burning was a single treatment as was direct drilling and stubble retention. Similarly the studies of Donovan et al. (2006) reported greater suppression of take-all with stubble retention and zero-tillage compared with stubble burning and conventional cultivation, in soils from Warialda and Croppa Creek (northern NSW), but the study did not permit separation of tillage and stubble effects.

In conclusion, retention of stubbles on the soil surface may promote some diseases of wheat. The best approach to reducing this problem will be increasing resistance genetically through breeding and reducing scope for infection through judicious agronomy, such as targeted rotational sequences.

3.4 Pests and Stubble Retention

Mice (*Mus domesticus*) have been a sporadic problem in Australian dryland cropping systems. Mouse numbers can build up as a result of favourable spring and early summer conditions leading to high mouse numbers in early autumn (Ylonen et al., 2003). The retention of stubble may provide some cover for mice. Chambers et al. (1996) reported mouse numbers were highest in grassed verges and in sorghum crops and stubbles in the Darling Downs in May and June. However, the effect of autumn stubble burning compared with stubble retention on mouse populations in southern cropping areas was unclear, with mouse damage to young seedlings of wheat in 1984 noted in both stubble-retained and stubble-burnt plots at Condobolin, NSW (Fettell pers. comm.). However, there were suggestions that no-till, stubble retention and associated possible increased cropping frequency may make mouse plagues more frequent (Brown, 2002).

The retention of stubble residues (rather than burning) has resulted in increased crop damage by Mediterranean snails, *Theba pisana*, *Cernuella virgata*, *Cochlicella* acuta and *Cochlicella barbara* (Baker, 1989, 1996). They cause significant damage during winter and spring from feeding, and also through grain contamination, due to their aestivation on the ears of cereals and pods of canola. However, the problem seems to be confined to alkaline soils in SA and grain contamination by *Cernuella virgata* was worse in years with high rainfall in the preceding autumn or in both autumn and spring (Carne-Cavagnaro et al., 2006).

Stubble burning was an effective control but has now been replaced with limited burning of windrows of canola stubble, baiting, rolling stubble to either crush the snails or to place them on the ground where they were destroyed by the hot conditions over summer.

3.5 Effect of Stubble Retention or Burning on Weed Populations

Conservation farming systems rely on herbicides to replace cultivation for the control of weeds. There were few instances in the literature of stubble retention, compared with stubble burning, resulting in a greater weed problem. This may be because the wide use of herbicides is effective in controlling any weed which resulted from sustained stubble retention. However, there is potential for stubble burning to reduce viable seed numbers on the soil surface and for stubble to interfere with herbicide application.

At Wagga Wagga, NSW, great brome grass (*Bromus diandrus* Roth) increased in stubble-retained systems (Heenan et al., 1994; Heenan et al., 1990). Burning stubble in the wheat/lupin system reduced infestation by 96% in the wheat phase in June 1986 (Table 17). The greatest infestation occurred where direct-drilled wheat followed wheat with stubble retained (Heenan et al., 1990). This occurred despite heavy use of herbicides; glyphosate pre-sowing, diclofop-methyl and bromoxynil post-emergent to wheat, and simazine immediately post-sowing of lupins. Fluazifop-P and diclofop-methyl were applied as required. In 1988 and 1989, delayed sowing, combined with glyphosate use before sowing, and hand weeding after sowing, successfully controlled giant brome in the experiment (Heenan et al., 1994).

Table 18 highlights the increase in the density of annual ryegrass (*Lolium rigidum*) in a long-term stubble retention experiment with continuous wheat cropping at Condobolin in central western NSW (Fettell, 1997; Fettell and Gill, 1995). In this experiment the combination of conventional cultivation and stubble retention (with stubble incorporated), gave maximum densities, compared with direct drilling and stubble burning. However, even with direct drilling, retaining stubble rather than burning stubble enhanced the density of ryegrass.

Downy brome (*Bromus tectorum* L.) has also been a problem in stubble-retained systems in North America. Wicks (1983) suggested that downy brome flourished with stubble mulching due to reduced evaporation providing a favourable site for germination. However, in a study in Oregon, burning of stubble resulted in a limited and non-significant reduction of downy brome populations (114 vs 356 plant/m^2) and growth (430 vs 740 kg/ha of dry matter, Rasmussen, 1995). Subsequent research (Ball et al., 1998) established that burning reduced the downy brome seed bank and downy brome plant density in wheat crops.

Wicks (1983) suggested that downy brome could be controlled in a winter wheat/fallow rotation if development of seed was prevented by using herbicides to prevent seeding during the fallow period and by delayed sowing of wheat.

Table 17. Effects of stubble management and tillage treatments on the density of great brome (plants/m^2) in the wheat phase of lupin-wheat rotations in June 1986 at Wagga Wagga, NSW.

Stubble management	Direct drilling (plants/m^2)	1 cultivation (plants/m^2)	3 cultivations (plants/m^2)	Mean (plants/m^2)
Retained	11.7 (*1.94*)[1]	13.5 (*1.5*)	4.2 (*1.39*)	9.8 (*1.61*)
Burnt	0.0 (*0*)	1.0 (*0.55*)	0.0 (*0*)	0.4 (*0.18*)
Mean	5.9 (*0.97*)	7.3 (*1.03*)	2.1 (*0.69*)	5.1 (*0.61*)
		lsd[2] (p = 0.05)		
Stubble means (S)		(*1.14*)		
Tillage means (T)		ns[3]		
S x T		ns		

Source: Heenan et al. (1990), reprinted with permission[26].

[1] Log (x + 1) transformations are in parentheses.

[2] lsd= least significant difference.

[3] ns = not significant.

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[26] ©CSIRO Publishing, Collingwood Vic (1990), 2 Oct 2009

Table 18. Effects of stubble management and tillage treatments on the density of annual ryegrass (plants/m^2) in long-term continuous wheat experiment at Condobolin, central western NSW.

	August 1993		June 1995	
Stubble management	Direct drilling (plants/m^2)	Cultivation (plants/m^2)	Direct drilling (plants/m^2)	Cultivation (plants/m^2)
Retained	2	10	33	190
Burnt	0	1	1	4

Source: Fettell (1997), reprinted with permission[27].

Other grass weeds were also affected by stubble burning, either by direct destruction of weed seeds or by reductions of seed dormancy following fire. Wild oat (*Avena fatua*) seed bank at pre-sowing and its population in a subsequent crop (1973) in the UK were reduced following stubble burning to 2193 viable seeds/m^2 and 433 plants/m^2, respectively, compared 3180 viable seeds/m^2 and 539 plants/m^2 when stubble was removed (Wilson and Cussans, 1975). Burning also reduced dormancy of seeds. Seeds recovered from the soil surface soon after burning were 82% non-dormant, compared with < 2% where stubble was not burnt (Wilson and Cussans, 1975).

Burning of stubble has contributed to the control of black-grass (*Alopecurus myosuroides* Huds) in the UK. Moss (1980) demonstrated that burning straw (compared with baling and straw removal) decreased the density of black-grass in a subsequent crop by 61 to 94 % depending on the quantity of stubble burnt (2.1 to 6.3 t/ha). Increasing amounts of stubble gave higher peak temperatures on the soil surface (143 to 270ºC), and longer duration of temperature in the burn (>200ºC for 0 to 35 seconds) and greater weed control. Prew et al. (1995) reported a build up of grass weeds, black-grass and sterile brome (*Bromus sterilis*) in a seven year study where straw was chopped and cultivated with tyned implements. Burning the stubble and ploughing reduced the build up by either destroying seed on the soil surface or burying seed. Prew et al. (1995) also suggested increased herbicide use was required to control these grass weeds.

Thus, stubble retention systems appear to favour some grass weeds by precluding burning as a weed control measure. Stubble retention appear to increase the need for grass weed control through the use of herbicides, but the efficacy of herbicides can be reduced by the presence of stubble.

3.6 Stubble Retention and Herbicide Application

The effectiveness of foliar application of herbicide to weeds may be reduced by the presence of stubble. The quantity of spray lodged on smooth pigweed (*Amaranthus hybridus* L.) was reduced by the presence of simulated standing wheaten stubble by 38% at a spray travel speed of 8 km/hr, and by 52% at 16 km/hr (Wolf et al., 2000). With giant foxtail (*Setaria faberi* Herrm.) as the target weed the comparable values were 9% and 36%. Wolf et al. (2000) proposed reduced speed of travel during spraying, and some adjustment of spray nozzles, as a means of partially improving application of spray to target plants in stubble. They also identified an electrostatic charge as beneficial. Thus, with a 50 cm nozzle spacing, a 45 kV

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[27] ©Kondinin Group, Perth WA (1997), 28 Sep 2009

electrostatic charge increased spray quantity by 96% on smooth pigweed and 345% on giant foxtail

Soil applied herbicides also may have their efficacy reduced by stubble. Metribuzin was retained by stubble and slowly released (Dao, 1991). Banks and Robinson (1982) applied metribuzin with a high volume boom spray application (280 L/ha of water) and found that greater than 30% of the herbicide reached the soil surface under 2.25 t/ha of wheaten straw, declining to less than 15% with 4.5 t/ha of straw and to less than 5% with 9 t/ha of straw. Subsequent watering (with 50 mm of simulated rainfall) increased these estimates to 45%, 39% and 35%, respectively.

Petersen and Shea (1985) found that emulsifiable concentrate (ec) formulated metolachlor was intercepted by stubble and subsequently leached with rainfall. More herbicide was intercepted with increasing amount of stubble, and some herbicide was lost from the stubble due to volatilization. A spray application of atrazine to wheaten stubble resulted in only 40% of the herbicide reaching the soil surface, with the stubble retaining about 60% of the atrazine applied (Ghadiri et al., 1984). The stubble (total load 6.4 t/ha) consisted of 3 t/ha of standing stubble, and 3.4 t/ha of flattened stubble. Three weeks after application and following 50 mm of rainfall, 75% of the original atrazine applied was in the surface 4 cm of soil, and 14% remained in the stubble.

A second issue was the difficulty of incorporating soil activated herbicides in no-till systems. Incorporation of trifluralin into soil is recommended in order to minimise losses of herbicide from breakdown due to UV light and volatilisation. Research undertaken in North America used granulated trifluralin applied to stubble without incorporation (Endres and Ahrens, 1995; Kirkland, 1996). The granules were presumed to move through the stubble to the soil surface more effectively than a liquid applied herbicide, likely aided by sowing or cultural disturbance. The granules were more effective than the ec formulation in control of foxtail (green foxtail, *Setaria viridis* L. and yellow foxtail, *S glauca* L.) with 86% vs 58% control in a tilled system, and 57% vs 22% in a later applied (November) untilled system (the untilled system had 7.5 t/ha of stubble with 84% ground cover, Endres and Ahrens, 1995). Control from earlier application (October) and no incorporation, was 76% compared with 81% from “incorporation” using a sweep cultivator.

Kirkland (1996) compared granulated trifluralin incorporated by a range of methods. All methods, including no incorporation, controlled green foxtail, while wild oats control (measured as plant density, panicle density and fresh weight) in a range of crops was not always improved by incorporation. Kirkland (1996) concluded that surface applied granular trifluralin would be of value in no-till agriculture. Endes and Ahrens (1995) suggest that trifluralin was effective as shading from the stubble may reduce UV breakdown of the herbicide and low temperatures in the stubble may minimise its volatilisation. The temperatures at application in October were 1 to 16ºC, and in the following weeks occasionally exceeded 10ºC; rainfall was minimal at one site (30 mm in 28 days after application). In Australia higher temperatures and higher UV radiation may mean that these practices are not transferable. Matic and Black (1990) have reported good control of rigid brome (*Bromus rigidus*) in SA using ec trifluralin incorporated with a direct drill sowing operation only.

Similar research has been conducted using granulated triallate application without incorporation into stubble-retained systems (Carlson and Morrow, 1986; Kirkland, 1994). Carlson and Morrow (1986) reported that triallate applied as granules at 1.4 kg/ha of active ingredient gave good control of wild oats, with 72% control with no incorporation compared with 75% where some incorporation had been used. These results suggest that problems associated with herbicide application for weed control in stubble-retained systems can be overcome.

3.7 Development of Herbicide Resistance in Weeds

Reliance of conservation farming systems on herbicides for weed control led to the evolution of herbicide resistant weeds in southern Australian cropping areas, particularly annual ryegrass (Gill and Holmes, 1997), wild oats (Nietschke et al., 1996) and wild radish (Raphanus raphanistrum L., Walsh et al., 2001). Broster and Pratley (2006) identified widespread herbicide resistance in annual ryegrass to a wide range of herbicide groups in the southern cropping areas. As indicated in Figure 22 resistance to group AI *(*diclofop-methyl, haloxyfop-R), group AII (clethodim, sethoxydim, tralkoxydim) and group B (chlorsulfuron, triasulfuron, imazapic/imazapyr) was also common, particularly in WA (Owen et al., 2007). Resistance to trifluralin was relatively common in the eastern states (Figure 22), while resistance to simazine (1% of total samples) and glyphosate (0.4% of samples) was also observed (Broster and Pratley, 2006). Multiple resistances were also present in annual ryegrass (Broster and Pratley, 2006; Neve et al., 2004; Owen et al., 2007).

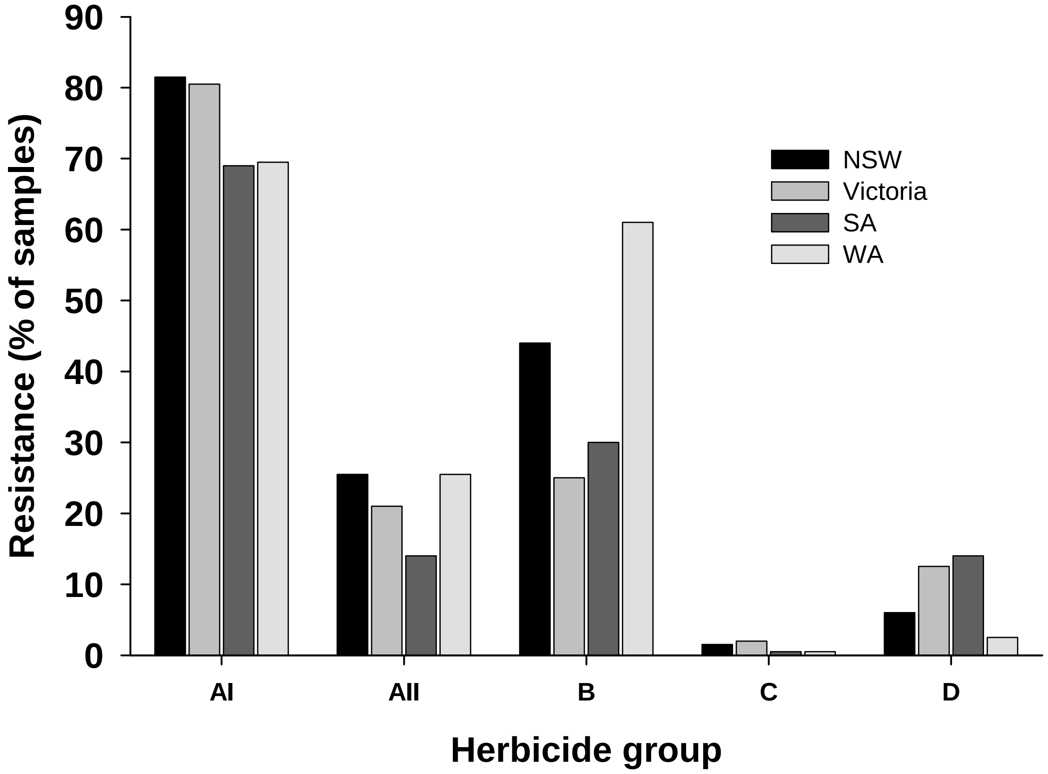

Figure 22. Frequency of resistance to five herbicide groups (AI, diclofop-methyl, haloxyfop-R; AII, Clethodim, sethoxydim, tralkoxydim; B, chlorsulfuron, triasulfuron, imazapic/imazapyr; C, simazine and D, trifluralin) in the southern cropping areas of Australia in annual rye grass samples submitted by farmers. Source: Broster and Pratley (2006), reprinted with permission[28].

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[28] ©CSIRO Publishing, Collingwood Vic (2006), 2 Oct 2009

The integrated management recommended for control of resistant weeds includes a phase of grazed pasture, non-selective herbicide use, delayed sowing, cutting of the crop for hay, increased crop density and competitiveness, the capture of weed seeds at harvest, the wider use of the herbicide trifluralin and a reversion to stubble burning (Gill and Holmes, 1997). Research has been conducted into other methods of weed control. Although the use of a pasture phase, alternating with a phase of cropping, is common practice in south-eastern Australia, it is not widely used in WA. Using an economic modelling assessment, Monjardino et al. (2004) suggested that a three year pasture phase (as opposed to the one year of pasture more commonly used in WA) may have a place in the management of herbicide resistance in weeds.

Another approach was to seek more competitive crop plants. This can be achieved agronomically with high seeding rates and by maintaining narrow row spacings. Working in southern NSW, Lemerle et al. (2004) found that higher populations of wheat (>200 plants/m^2) approximately halved the dry weight of annual ryegrass. Doubling wheat density from 100 wheat plants/m^2 to 200 plants/m^2, resulted in an average yield loss due to the presence of ryegrass of 23% and 17%, respectively. While different wheat cultivars were not used in these experiments, other research using a wider range of wheat genotypes demonstrated some difference in the competitiveness in wheat (Lemerle et al., 1996). In a subsequent review of crop competitiveness Lemerle et al. (2001) suggested that breeding a more competitive wheat cultivar may be advantageous, although competitive ability (CA) would need to be under genetic control, and the gene/s for CA must not impose a significant penalty on yield. Inability to identify simple traits reliably associated with CA (including leaf size, width and early vigour) will impede selection. More detailed field selection strategies have since been suggested (Lemerle et al., 2006).

A more direct approach may involve allelopathic effects from wheat targeting specific weeds. For example, allelochemicals in wheat tissue were found to exude into an artificial growth medium and inhibit root growth of ryegrass (Wu et al., 2002). Ryegrass root growth was negatively correlated with the concentration of *p*-hydroxybenzoic, vanillic, and *trans*-ferulic acids in root exudates. The allelopathic characteristic of 453 wheat genotypes against ryegrass was tested using a laboratory method and found to vary considerably from 10 to 91% inhibition of root growth.

3.8 Immobilisation of Nitrogen with Stubble Retention

Stubble retention can modify the N requirements of crops compared with stubble removal or burning. During wheat stubble decomposition, immobilisation of N is common, reducing the immediate availability of N to crops. Subsequent remineralisation of N derived from the stubble may augment N supply later in crop development, or in a subsequent crop.

Maximum N immobilisation from wheat straw are approximately 26-31 mg N/g C decomposed (Mary et al., 1996). Lower values (15-18 mg N/g C decomposed) have been recorded where N supply was limited (Reinertsen et al., 1984). Field determined values of net immobilisation covered a similar range of 12-33 mg N/g C decomposed (Mary et al., 1996). In a low N environment stubble decomposition may be slowed. 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.

The N source for decomposition can be the stubble itself, existing soil N, or fertiliser N. When in isolation the N in the stubble appeared to control the rate of decomposition (Figure 23). Where additional N was available the micro organisms decomposing the stubble will use this to increase microbial biomass, and so immobilise the N.

In a laboratory experiment using ^{15}N labelled soil and fertiliser, Smith and Sharpley (1990) found that wheat residues reduced mineral N, compared with a no residue control after 14 days incubation. They also found that the incorporation of wheaten stubble with soil reduced 'indigenous' mineral N originating from the soil to less than 50% of that in the no residue treatment. When stubble was left on the soil surface, indigenous mineral N in the soil was greater than 80% of the no residue control, indicating less immobilisation by the stubble. Availability of fertiliser-derived mineral N was reduced by 75% with incorporated of stubble, compared with 35% with surface applied stubble. The lower N immobilisation with stubble placement on the soil surface may have resulted from delayed decomposition of the stubble, possibly due to poorer soil/stubble contact compared with incorporated stubble. After 84 days incubation the mineral N in the soil from soil sources or fertiliser were similar, although the total amount of mineral N was still slightly lower with stubble than without.

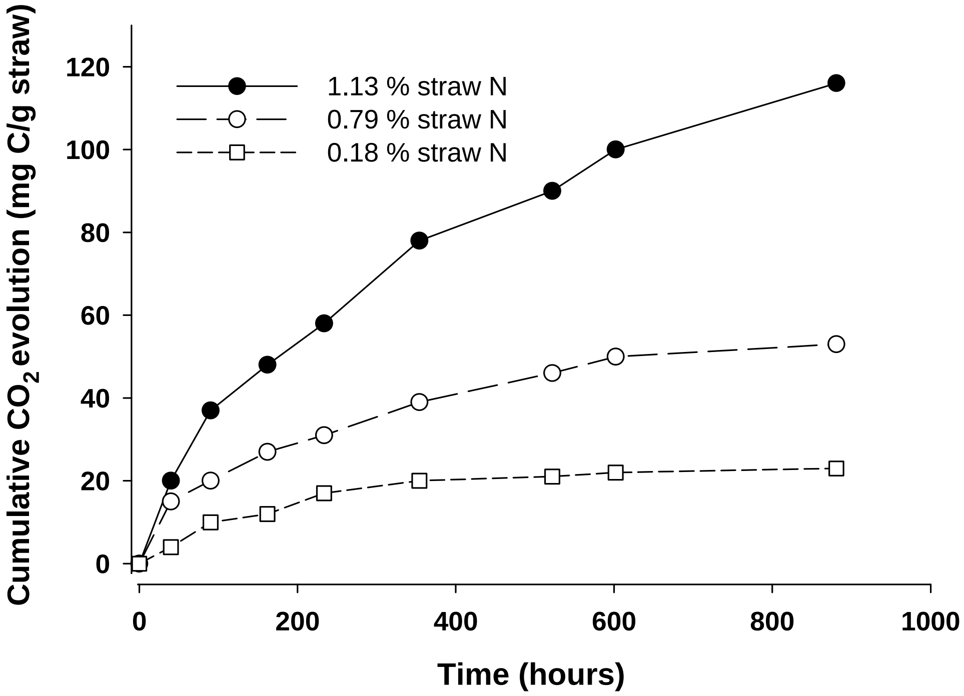

Figure 23. Cumulative carbon dioxide (CO_2) evolution from three wheat straws with 0.18%, 0.79% or 1.13% straw N and similar carbon concentrations (420-428 mg/g stubble) when incubated in sand. Source: Reinertsen et al. (1984), reprinted with permission[29].

Smith and Sharpley (Smith and Sharpley, 1993) used similar study methods to those discussed above, except that they labelled the stubble with ^{15}N, rather than the soil or fertiliser. Mineral N in the soil from the wheaten stubble was equivalent to 3 kg/ha at 14 days and 12.2 kg/ha at 168 days when stubble was incorporated; equivalent to 6 and 25% of the stubble N content, respectively. When stubble was applied to the surface, mineral N 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

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[29] ©Elsevier (1984), 2 Sept 2009

% of stubble N content). Residue-sourced N from incorporated wheaten stubble, and its utilisation by a subsequent crop, was followed in the field in Kansas, USA (Wagger et al., 1985). Between 12 and 15% of the N in the wheat stubble was mineralised in the following season. With a range of 15.4 to 20.2 kg total N /ha applied in the stubble, the amount of mineralised N over the season was approximately 2 to 3 kg/ha of N. This slow recycling of N was seen as a long-term benefit in stubble-retained systems.

However, microbial immobilisation of N during stubble decomposition competes with N demand by a crop. Often, additional fertiliser N is applied, both to meet the requirements of the growing crop and, to hasten stubble decomposition. Thomas et al. (1995) working on a long-term experiment at Billa Billa, Queensland made the observation that lower grain protein of wheat was associated with no-till and reduced tillage systems when combined with stubble retention. Generally, application of 60 N kg/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 under stubble-retained systems to ensure adequate N following immobilisation during early wheat growth.

Incorporation of stubble, compared with burning, occasionally increased the nitrogen (N) fertiliser requirement of the following wheat crop in three long-term experiments conducted in WA (Mason, 1992). The interaction between stubble treatment and N rate was significant at Wongan Hills in 2 years out of 10, and at Merredin in 3 of 10 years. Response to N fertiliser was higher where the stubble was incorporated than where it was burnt, and optimum economic rates of N fertiliser tended to be higher with stubble incorporation, although differences were small. Mason (1992) concluded that with stubble residues of 1-3 t/ha, stubble treatment was unlikely to be a major factor in determining the rate of N fertiliser required for a wheat crop.

These observations indicated increased demand for N in stubble-retained systems, although the demand may be reduced by retaining stubble on the surface to reduce N immobilisation. In the context of legume-cereal systems an aspect not well researched is the increased scope for nitrate leaching under long-term stubble retention systems. Part of the N benefit of legume crops to subsequent cereals involved nitrate accumulated in deeper soil horizons during legume growth (Evans et al., 2003). It is feasible that this nitrate may leach beyond the depth of the root system in stubble-retained systems with increased stored water and heavy rainfall.

3.9 Allelopathy and Retained Stubble

The presence of wheaten stubble can have negative effects on a newly sown crop, unrelated to disease, weed or nutritional problems. These effects have been ascribed to allelopathy. Allelochemicals were thought to leach from stubble early in decomposition of the stubble. Alternatively, these chemicals may be produced by the micro organisms present during the early stages of stubble decomposition.

Kimber (1967) made aqueous extracts from wheat straw, which had been decomposing for up to 6 weeks, and demonstrated that geminating seedlings of wheat and oats were adversely affected by the leachate under aseptic conditions. The effects were more pronounced on the roots than shoots and were a maximum after two to six days of decomposition. Prolonged storage of stubble in a shed or weathering in the field reduced these inhibitions.

Subsequent research confirmed the earlier observations of greater effects on the roots than shoots, and that the inhibition of root growth and germination decreased the longer the period of decomposition of crop residues (Kimber, 1973a). Further the inhibition depended on plant maturity (with green being more inhibitory than mature), type of residue and the extent of weathering. Working in soil, in pots, Kimber (1973b) established that mineral nitrogen addition could not fully overcome the effects of wheat straw on wheat germination and subsequent wheat yield, and that straw placed on the soil surface at an equivalent rate of approximately 5 t/ha was more damaging to wheat germination than treatments where the soil and straw were mixed prior to sowing.

Dias (1991) mixed soil and stubble of wheat or oats and subsequently separated soil and stubble after 0, 14, 21, 43 and 63 days. Aqueous extracts were produced from both soil and stubble components and tested against germination of wheat, oats and subterranean clover. Straw extracts delayed germination and reduced root growth, with close agreement between the two effects. Soil extracts generally had a lesser impact. Extracts from wheat and oats were not substantially different and while their effect on subterranean clover was stimulatory, it was inhibitory on wheat and oats. These effects varied with time of incubation of soil and stubble in an apparently cyclical fashion, suggesting that allelochemicals were produced at various stages of decomposition. Dias (1991), however, concluded that these allelopathic effects were unlikely to be important in the field.

Field, glasshouse and laboratory studies demonstrated that residues from *Brassica* species had differential effects on wheat (Mason-Sedun et al., 1986). Aqueous extracts of thirteen *Brassica* residues from 6 species showed differential effects on reducing coleoptile length (57-91%) and root growth (59-98%) when applied at an equivalent of 5.5 t/ha and incorporated into the soil 4 weeks prior to planting. The residues had been field grown on the site and field weathered for a short time between harvest (December 28, 1983) and sowing (January 21, 1984). In the field six cultivars of four species all reduced grain yield, plant dry matter, height and tiller number in wheat. However, the effects due to Brassica species were different and in order of increasing inhibition were *B. rapa* (cv Torch), *B. juncea* (cv Zem 1), *B. napus* (cv Wesroona), *B. niger* (cv Vince) and *B. juncea* (cvs Lethbridge 22a and Zem 2). There were significant positive correlations between field and laboratory results.

Purvis (1990) demonstrated inhibition of wheat growth by stubbles of crops, in descending order of inhibition, of sorghum (*Sorghum bicolor* (L.) Moench), sunflower (*Helianthus annuus* L.), oilseed rape (*Brassica napus* L.), wheat and field pea (*Pisum sativum* L.). Stubbles were collected, stored for up to 6 months, applied at the rate of 5 t/ha and incorporated by rotary hoe to a depth of 10 cm (1982), or grown on the plots (1983 stubbles), with stubble loads adjusted to 5 t/ha. All stubbles reduced germination of wheat, although growth and grain yield was most affected by sorghum stubbles in 1982. In 1983, grain yield was greater with previous or current stubble as compared with no stubble, and pea and rape stubbles had the greatest effect. Purvis (1990) interpreted the effects in 1983 to be due to a longer exposure to rainfall on the stubbles as compared with 1982. In a series of glasshouse experiments Purvis and Jones (1990) demonstrated that there was intraspecific variability in inhibition of wheat in both sorghum and sunflower. Inhibition of wheat emergence ranged from 10 to 31% for sorghum genotypes, and from 4 to 33% for sunflower genotypes.

The intra specific variability in rapeseed (Dias, 1991) and in sorghum and sunflower (Purvis and Jones, 1990), suggested that it may be possible to breed for cultivars with lower potential for allelopathic damage to crops sown into their stubbles. In the field these effects were related to stubble decomposition, as most observers indicated that fresh stubble in the early stages of decomposition has the greatest potential for crop damage. However, few attempts have been made to relate stubble decomposition to allelopathic potential. Mature but unleached cereal straw contains a water soluble fraction. Harper and Lynch (1982) extracted the hot water soluble components of cereal straw and found that 8.5% by weight of wheaten and barley and 11.8% of oaten straw was extractable. In a separate extraction Harper and Lynch (1981) found that 7.3% of oaten straw was extractable. The extractants were 27 to 36% C and 1.5 to 2.5% N, and this represented 5.2 to 9.7% of the C in cereal straw and 46 to 64% of the N. The most easily extracted material, from the first stages of decomposition, had a lower C:N ratio (range 12 to 21) than the original straw (approximately 100-140), because of the relatively higher water solubility of the N in the straw. The expectation would be of a rapid first phase of decomposition with approximately 10% loss of straw weight due to removal of the water soluble component. The leached material with a relatively higher C:N ratio may then encourage rapid microbial growth if conditions were otherwise suitable. The suggestion was that the early phase of allelopathy may be directly due to the water soluble components from stubble, or to their effect in stimulating microbial growth.

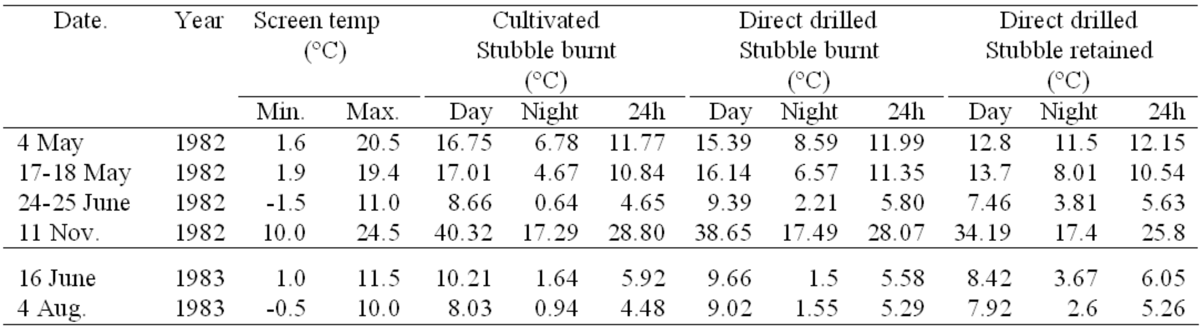
Cook and Haglund (1991), working in Washington State, identified cereal diseases as responsible for crop ill health in a continuous wheat cropping system, rather than allelopathy. They found grain yield responses to soil fumigation when wheat followed wheat and the stubbles were not burnt. In other experiments they found grain yield response to stubble removal and to fumigation of the soil, but not to fumigation of the retained straw. They identified the diseases take-all, *Rhizoctonia* and *Pythium*, and claimed that the soil fumigation controlled these diseases. Alternatively, when stubble is placed on the soil surface, leaching of the soluble fraction into the soil may lead to a burst of microbial activity and release of phytotoxins. This microbial response may be reduced if the soil was prior-sterilized by fumigation.

The opportunity for decomposition of allelopathic chemicals may be minimised by dry summer conditions in southern Australia and, although seasonally variable, this may increase allelopathic effects on newly sown wheat in stubble-retained systems. There appears to be potential to mitigate allelopathic effects through genetic manipulation of crops and through improved crop sequencing.

3.10 Physical Effects of Retained Stubble

Stubble mulch can influence the microclimate experienced by a newly sown crop. Aston and Fischer (1986) compared several tillage and stubble management treatments on soil temperature and early crop growth at Murrumbateman, NSW in 1982 (characterised by a dry season and cold winter) and 1983 (when conditions were wetter and warmer). The plots had stubble loads of 4 t/ha of stubble in 1982 and 2 t/ha in 1983. In 1983 additional stubble was added to achieve the 4 t/ha stubble amount. The cultivated treatment and the no-stubble-direct drilled treatment were sown with full soil disturbance, while the stubble-retained treatment was sown with narrower sowing points (i.e. no-till or zero-till). Straw was removed from the stubble-retained plots prior to sowing, and returned to the plots immediately after sowing (as a stubble mulch). The presence of stubble mulch reduced the daily range of temperature in winter compared with a direct drilled treatment with no mulch and the cultivated treatment (Table 19). The authors considered that this resulted in a longer period of cooler temperatures during winter in the stubble treatment. They presented degree day estimates using a threshold temperature of 4ºC (Table 20) and concluded that the lower estimates under the stubble mulch may be a contributing factor to slow early growth with stubble retention. The difference in degree days for the direct drilled treatments were larger in the cold season of 1982 (4.03 *vs* 3.41; no mulch *vs* mulch) than in the warmer 1983 season (3.7 *vs* 3.6). If cold under a stubble mulch in winter was a problem for crop growth, then the colder conditions in central and southern parts of NSW and north-eastern Victoria would exacerbate this problem. The wheat belt in these areas has average July minimum temperatures of between 0 and 3ºC, while other areas of cropping in Australia have a range between 3 and 6ºC, with some areas of northern WA and coastal areas of SA between 6 and 9ºC (Figure 24).

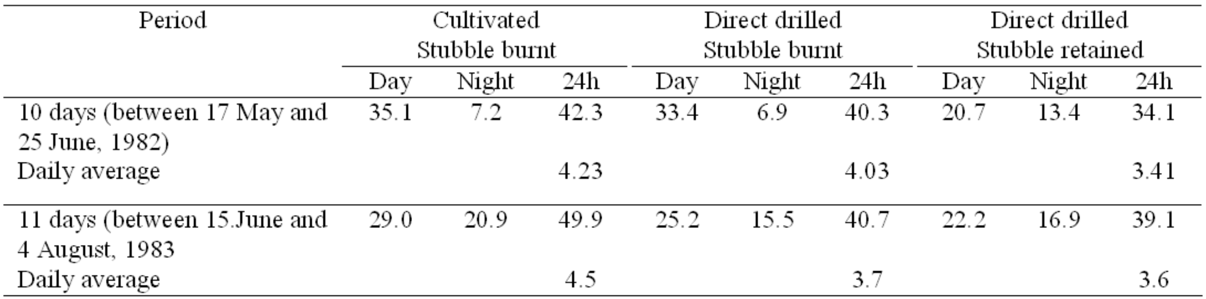
Table 19. Mean daytime, night-time and 24 h soil temperatures measured at a depth of 1 cm in three tillage treatments on selected days in 1982 and 1983.



Date.	Year	Screen temp (°C)		Cultivated Stubble burnt (°C)			Direct drilled Stubble burnt (°C)			Direct drilled Stubble retained (°C)		
		Min.	Max.	Day	Night	24h	Day	Night	24h	Day	Night	24h
4 May	1982	1.6	20.5	16.75	6.78	11.77	15.39	8.59	11.99	12.8	11.5	12.15
17-18 May	1982	1.9	19.4	17.01	4.67	10.84	16.14	6.57	11.35	13.7	8.01	10.54
24-25 June	1982	-1.5	11.0	8.66	0.64	4.65	9.39	2.21	5.80	7.46	3.81	5.63
11 Nov.	1982	10.0	24.5	40.32	17.29	28.80	38.65	17.49	28.07	34.19	17.4	25.8
16 June	1983	1.0	11.5	10.21	1.64	5.92	9.66	1.5	5.58	8.42	3.67	6.05
4 Aug.	1983	-0.5	10.0	8.03	0.94	4.48	9.02	1.55	5.29	7.92	2.6	5.26

Source: Aston and Fischer (1986), reprinted with permission[30].

Table 20. Heat sums of day (10 h), night (14 h) and 24 h periods from the soil surface to a depth of 1 cm above a base temperature of 4ºC in three treatments over a number of days in 1982 and 1983, with heat sums expressed in degree days.



Period	Cultivated Stubble burnt			Direct drilled Stubble burnt			Direct drilled Stubble retained		
	Day	Night	24h	Day	Night	24h	Day	Night	24h
10 days (between 17 May and 25 June, 1982)	35.1	7.2	42.3	33.4	6.9	40.3	20.7	13.4	34.1
Daily average			4.23			4.03			3.41
11 days (between 15.June and 4 August, 1983	29.0	20.9	49.9	25.2	15.5	40.7	22.2	16.9	39.1
Daily average			4.5			3.7			3.6

Source: Aston and Fischer (1986), reprinted with permission[30].

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[30] ©CSIRO Publishing, Collingwood Vic (1990), 2 Oct 2009

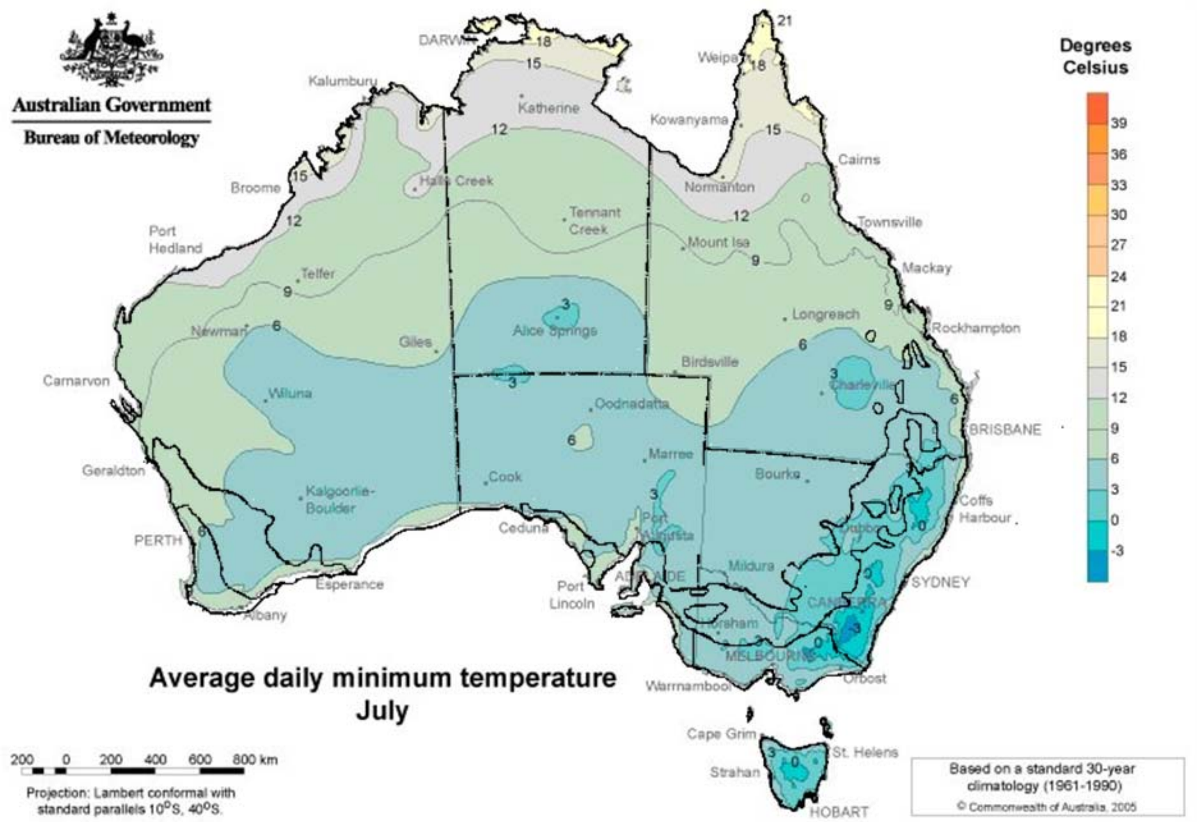

Figure 24. Average daily July minimum temperature over 30 years (1961-1990) for Australia (Source: Australian Bureau of Meteorology, reproduced with permission[31]) with an overlay of wheat cropping areas of Australia added from Cramb (2000).

Stubble retention in North America is associated with snow capture and with a rise in soil temperature in spring (Flerchinger et al., 2003). However, although low soil temperatures were recorded in tall standing stubble in Canada, sowing into tall stubble has been associated with increased yield, compared with cultivated stubble, in wheat (Cutforth and McConkey, 1997), pulses (Cutforth et al., 2002) and canola (Cutforth et al., 2006). Growing season evapotranspiration was not affected by stubble height, but wheat sown into tall standing stubble was shown to transpire a greater proportion of evapotranspiration (Cutforth and McConkey, 1997). Consideration of stubble height led to studies on harvesting height in relation to tiller density and effects on wind speed (McMaster et al., 2000).

Wilkins et al. (1988), working in Oregon, USA, found that a standing wheat stubble lowered the soil temperature and reduced photosynthetically active radiation when compared with no stubble or a reduced stubble load. In the presence of stubble, by tillering there were reductions in dry matter yield, leaf development and plant height. The authors recommended removal or reduction of “excess” stubble prior to sowing to obtain good early growth of wheat.

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[31] ©Commonwealth of Australia (2009), 3 Sept 2009

Growth of canola is particularly sensitive to stubble residues. At five sites in southern NSW, Bruce et al. (2005) found adverse effects on canola establishment (mean reduction 33%), vegetative biomass (56%) and yield (23%) where 5-6 t/ha of wheaten stubble was added to the plots after sowing. Allelopathy may have been involved at one site, but there was no correlation between laboratory assessed phytotoxicity of different wheat cultivars contributing the stubble and canola growth at the other four sites. Temperature effects and light penetration were identified as possible effects. Temperature at 1 cm above the stubble had a lower minimum temperature for a day in July than occurred at 1 cm above the soil surface in the nil stubble treatment. At the coldest site (Ginninderra, ACT) the differences were greater (3.8ºC) when the minimum temperature above the stubble was - 6.8ºC, although there were no differences when temperature above the stubble was higher (7ºC). The authors indicated that low temperature above the stubble could be a partial contributor to slow early growth of canola.

A subsequent experiment by Bruce et al. (2006a) also demonstrated that surface-retained wheat stubble (5 t/ha) reduced canola vegetative biomass (46%) and yield of grain (26%). There was no effect of wheat variety or stage of stubble decomposition on canola growth and yield. Inert plastic mulch designed to simulate the physical effects of wheaten stubble had a similar effect on growth and yield as wheaten stubble. The authors concluded that growth reduction was associated with the physical impact of the stubble, including a reduction in photosynthetically active radiation, the red:far red ratio of incident light under the stubble, and the temperature above the stubble layer. These effects resulted in elongated hypocotyls, delayed emergence, slower leaf area development and increased seedling disease. Further research in pots demonstrated that plants with greater hypocotyl elongation had smaller root systems, less leaf area and less shoot and root biomass (Bruce et al., 2006b). The authors suggested that the effect of stubble in the field was to cause a re-allocation of resources in the canola plant to the growth of the hypocotyl, which was a physical rather than biochemical effect of the stubble.

Bruce et al. (2006c) examined the benefit of moving wheaten stubble to the inter row space at sowing to remove the constraints on canola emergence and growth. Of the four field sites studied, canola density at harvest was improved at one site (Greenthorpe 1) compared with the stubble spread treatment; yield was improved at two sites (Greenthorpe 1 and 2, Table 21). However, the authors claimed that, averaged over all sites, the stubble inter row treatment showed a yield reduction of 5.3% compared with the no stubble treatment. Examination of the data (Table 21) showed a yield reduction of 5.7% at Greenethorpe 1, 18.4% at Ginninderra and 31.9% at Greenethorpe 2. This excluded the non-significant and anomalous data from Harden where the stubble removal treatment had a lower yield that either of the stubble-retained systems, a result inconsistent with the rest of the study. This suggested that inter row displacement of stubble at sowing was at best only a partial answer to the management of wheaten stubble when sowing canola.

Table 21. Canola plant density (plants/m^2) at harvest and grain yield (t/ha) at four sites in southern New South Wales with various treatments of a 6 t/ha wheaten stubble.

Site	Measurement	Stubble burnt	Stubble removed	Stubble inter row	Stubble spread	sed[1]
Greenethorpe 1	Plant density (plants/m^2)	44	45	35	22	4.3
	Yield (t/ha)	3.1	3.5	3.3	2.3	0.3
Greenethorpe 2	Plant density (plants/m^2)	na[2]	27	17	13	ns[3]
	Yield (t/ha)	na	2.2	1.5	0.9	0.2
Ginninderra	Plant density (plants/m^2)	na	99	57	70	6
	Yield (t/ha)	na	6.0	4.9	4.2	0.4
Harden	Plant density (plants/m^2)	na	49	39	29	6
	Yield (t/ha)	na	3.5	4.6	3.8	ns

Source: Bruce et al. (2006), reprinted with permission[32].
[1]sed = standard error of difference.
[2]na = not available.
[3]ns = not significant

Reithmuller et al. (2003) used large seed of canola to address problems they anticipated with variable depth of sowing and the adoption of stubble retention. While they identified advantages in using larger seed of canola (1.7 to 2mm in diameter depending on experiment) at two sites, for plant establishment, yield and oil content, there was no advantage of larger seed in the field under stubble retention compared with stubble removal. The quantity of stubble present was not reported. In a glasshouse experiment using 2.5 and 5 t/ha equivalent of cereal stubble there was no effect of stubble other than to increase seedling height, as plants appeared to etiolate.

Similar problems with poor depth control and emergence through stubble have been investigated in wheat (Rebetzke et al., 2005). Longer coleoptiles in wheat would be expected to improve seedling emergence if sowing depth was deep and/od stubble load was heavy. Rebetzke et al. (2005) varied depth of sowing and stubble in glasshouse and field experiments. They identified that cultivars of wheat with a short coleoptile were slower to emerge and had reduced tiller number and biomass compared with wheat genotypes with longer coleoptiles. They suggested that variation for coleoptile length, independent of gibberellin-responsive dwarfing genes (for example, Rht8), would allow the breeding of semi dwarf wheats with longer coleoptiles which would better suit a stubble-retained farming system.

Thus, the physical effects of stubble on plant growth may be combated by genetic improvements for coleoptile length and cold tolerance and by displacement of stubble from the immediate row of emerging seedlings.

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[32] ©CSIRO Publishing, Collingwood Vic (2006), 2 Oct 2009

3.11 Stratification of the Soil Profile

3.11.1 Soil pH

Retention of stubble may result in greater surface soil acidification under direct drilling systems. For example, in a long-term crop rotation experiment at Wagga Wagga, NSW in a wheat/lupin system, on a soil prone to acidification, the 0-10 cm depth was approximately 0.20 pH_{Ca} units lower (pH in 0.01 mol/L $CaCl_2$) than with stubble burning (Figure 25A). This effect was established approximately 12 years after the experiment began and has been maintained until about 2000 (Conyers et al., 2003; Heenan and Taylor, 1995). Similarly, in SA (Xu et al., 2002) soil pH_{Ca} (0-10 cm) declined after 15 years under stubble retention to about 4.8 pH_{Ca} compared with about 5.1 pH_{Ca} with stubble burning/removal. The rotation was wheat/lupin with no added fertiliser N, with the stubble removal treatment being stubble burnt for 11 years, and removed in the subsequent 5 years.

As shown in Figure 25B, acidification appeared to be limited to the surface 0-5 cm layer of soil (Conyers et al., 1996). The most acidic soil in the profile was at 5-10 cm depth irrespective of stubble management, as a result of the cessation of tillage. The ash from burning stubble is alkaline, being partly K_2O, CaO and MgO, which will give a rapid increase in the pH of the surface soil. In the longer term the decomposition of the stubble will have a similar effect, but the difference was in the fate of the N component of the stubble. With stubble burning N was lost to the atmosphere. With a wheat/lupin system this N was originally derived from atmospheric N and would have no net effect on soil profile acidification. With stubble retention, organic N may be converted to nitrate in the surface soil and leached below that layer, resulting in acidification of the layer. In many instances this nitrate may be taken up from depth in the soil, giving net addition of alkalinity at that deeper layer, and redistribution of alkalinity within the soil profile. However, if nitrate is leached below the rooting depth of plants there is an acidification in the soil surface, which is not offset by any addition of alkalinity at depth.

The difference in pH of 0.2 pH_{Ca} units (Figure 25A) could be amended with approximately 300 kg/ha of lime. If the pH difference was generated over 12 years, about 25 kg/ha/year of additional lime would be required for the stubble retention system. In SA (Xu et al., 2002) the stubble retention treatment would require about 21 kg/ha/year of lime to match the lower acidification rate of burning/removal treatment (1.36 compared with 1.78 kmol H^+/ha/yr). This was a cost of having more mineral N on offer to crops in the stubble retention system, mainly because every second crop was lupin (lupin stubble was burnt in the ‘burn treatment’). In this stubble retention system maintaining acidity nearer to the soil surface facilitated its treatment with lime, although with no-tillage the effect of lime took longer to move down the soil profile (Conyers et al., 2003).

Effects of ash from burning stubble have been observed in WA in a study over 33 sites (Brennan et al., 2003). “Waves” of good and poor growth were observed in cereal crops following a canola crop. When swaths from a canola crop were burnt, growth of the subsequent cereal crop was enhanced. This was identified as due to increased K in the soil under the canola swath (in 23 sites), and also to increased soil pH induced by the ash from canola stubble. Responses to molybdenum were observed in the cereal crop between swathes where the soil was more acidic, but not in the swathed area (16 sites).

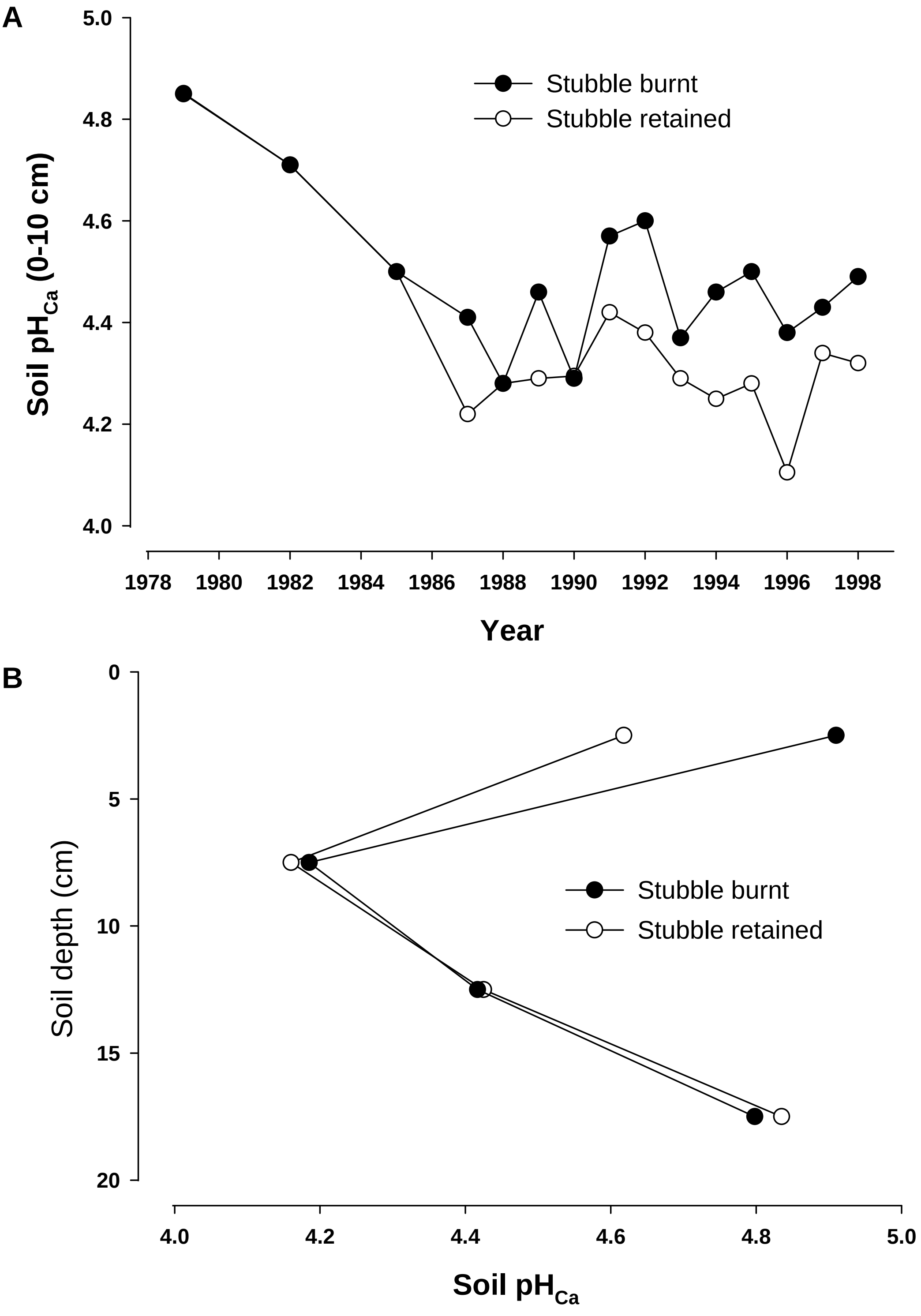

Figure 25. The pH_{Ca} of soil showing the effect of stubble burning and stubble retention (A) with years in the 0-10 cm depth, Source: Heenan and Conyers (2000), reprinted with permission[33] and (B) with depth in the soil at Wagga Wagga, NSW in 1991, Source: Conyers et al. (1996), reprinted with permission[34].

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[33] ©Kondinin Group, Perth WA (2000), 18 Sep 2009

[34] ©Elsevier (1996), 2 Sept 2009

3.11.2 Plant nutrients and stubble retention or burning

Direct drilled and no-tilled systems accumulated some immobile nutrients in the soil surface. In traditional cultivated systems approximately 10 cm of the surface soil was mixed by cultivation.

Surface accumulation of phosphorus (P) was of particular concern and Zibilske et al. (2002) identified this redistribution in Texas after nine years of a cotton/corn cropping system. Zibilske et al. (2002) suggested that the surface accumulation was at the expense of deeper soil P, which was "mined" (Figure 26A). Salinas-Garcia et al. (2002) identified the same surface accumulation in a no-till corn system in Mexico compared with fallow/corn system (Figure 26B). Similar effects were reported in Australia in wheat cropping systems in Queensland and southern NSW (Table 22).

Cornish (1987) found that surface accumulated soil P was less plant available and, as a result, direct drilled wheat was more responsive to applied P and needed higher rates of fertiliser P to achieve 90% of maximum yield than wheat grown in cultivated soils. This could be due to surface drying making surface P less available or to slower early root growth in direct drilled crops. Similarly, it has been suggested, that soil zinc (Zn), copper (Cu) and manganese (Mn) may accumulate in the soil surface and be less plant available (Asghar et al., 1996).

This concentration of nutrients to surface layers results from minimal soil mixing in direct drill or no-till systems. However, from the point of view of the current review, the role of stubble retention in nutrient distribution in soil was less clear. It could be assumed that as a result of SOC stratification accentuated in the soil surface with stubble retention, as compared with stubble burning (Table 15), some nutrients which are immobile in the soil would behave similarly. However, in sustained systems, nutrients are taken to the soil surface by plant growth and whether this plant growth decomposes (stubble retention) or is burnt should have only a marginal effect. A difference would be with N and sulphur (S), which are lost in burn systems, whilst in a stubble-retained system both nitrate and sulphate produced from mineralisation in the organic surface layer are mobile in the soil and leach downwards from the surface soil.

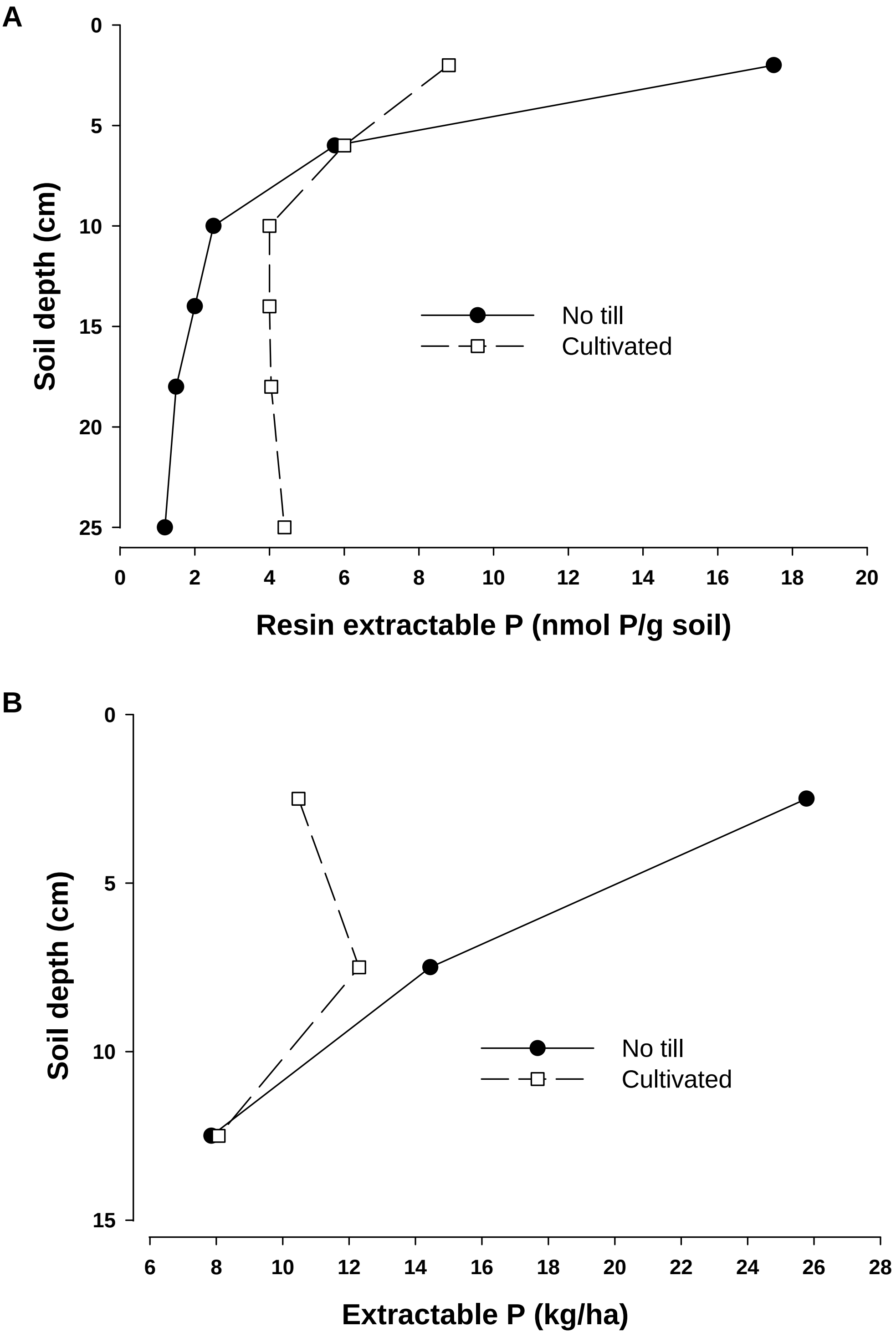

Figure 26. The distribution of soil P with depth for no-till and conventionally cultivated treatments (A) nine years after the commencement of the tillage treatments in a cotton/corn double crop system in Texas, Source: Zibilske et al. (2002), reprinted with permission[35] and (B) averaged over four sites after six years for a fallow/corn system in central western Mexico, Adapted from; Salinas-Garcia et al. (2002).

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[35] ©Elsevier (2002), 2 Sept 2009

Table 22. The distribution of nutrients in the surface soil after 10 years of direct drilling (DD) at Wagga Wagga, NSW compared with ten years of conventional cultivation (CC) or eight years of no-till (NT) in Brigalow, Queensland and after a single rotary hoe cultivation (Cult).

Depth	Wagga Wagga		Brigalow Research Station					
(cm)	P (Colwell, mg/kg)		P (Colwell, mg/kg)		Replaceable K (cmol(+)/kg)		Zn (0.005 M DTPA, mg/kg)	
	CC	DD	Cult	NT	Cult	NT	Cult	NT
0-5	22	35	38.7	47.2	0.76	0.94	na	0.97
5-10	24	16	36.7	27.6	0.72	0.55	na	0.77
10-15	na	na	20.8	16.3	0.42	0.35	na	0.47
15-20	na	na	12.0	10.7	0.27	0.25	na	0.43

Data for Wagga Wagga, NSW Adapted from: Cornish (1987).
Data for Brigalow Research Station adapted from: Asghar et al. (1996).
na = not available

Bolland and Brennan (2006) suggest that P, Cu and Zn applied as fertiliser to overcome deficiencies would be mixed throughout the cultivation layer in the earlier cultivation systems. However, with direct drilling these immobile nutrients would remain in the area of the fertiliser band and be less effective as residual fertilisers for subsequent crops. They suggest 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 in the cultivated crop and any subsequent no-till crops. In their experiments (46 experiments over 16 sites with many drought affected) yields of grain were generally greater where the soil had been cultivated prior to sowing, compared with maintaining a direct drilled sowing regime. However, this did not appear to be due to increased availability of P, Cu or Zn as a response to application of these nutrients occurred at only one site.

Similarly, Asghar et al. (1996) reported increased nutrient uptake and an increase in grain yield (28%) following their single cultivation of a long-term no-till system, when compared with maintaining no-till. They suggest that the practice of occasional cultivation in “no-till” systems may need to be accepted as part of “conservation tillage”.

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 (cultivation) to the conservation farming system. Pierce et al. (1994) working in corn cropping in Michigan, USA, cultivated plots which had been in long-term no-till and monitored these areas for up to five years of subsequent no-till. They found that most soil properties including P and potassium (K) distribution, returned to match treatments maintained in a continuous no-till system. However, the C and N in the soil surface were lower than in the continuous no-till treatment.

In conclusion, if stubble retention was used in conjunction with either direct drill, no-till or zero-till then the residual value of immobile nutrients such as P may be reduced. This may necessitate corrective action through additional fertiliser, or mechanical redistribution of nutrients through some form of cultivation.

4. EFFECTS OF STUBBLE RETENTION ON CROP YIELD

The effects of stubble retention on yield of grain in Australia were reviewed by Kirkegaard (1995). Using yield difference (Ydiff = yield with stubble retained-yield with stubble burnt/removed), Kirkegaard (1995) found that, on average over all regions, stubble retention reduced crop yield relative to stubble burning or removal (Table 23). In summary, the problems associated with stubble retention have generally appeared to outweigh the benefits in the context of wheat production. These were in contrast to the comparison between cultivation and direct drilling/no-tillage, where the effects of tillage were smaller between regions and could be slightly positive or negative. However, the observation can be made that within regions the yield losses due to stubble retention were ranked as Victoria<WA<Queensland and northern NSW<southern NSW. Queensland and northern NSW and WA had the greatest adoption of stubble retention and had small yield losses. Southern NSW has more substantial yield loss, which was inconsistent with the smaller yield losses in adjacent north-eastern Victoria (Rutherglen).

Kirkegaard (1995) examined two hypotheses:

1. yield benefits of stubble retention increase with the number of years that treatments were imposed, presumably due to the improvements in soil conditions on those treatments; and

2. yield are improved from stubble retention in dry environments (both regions and seasons) due to improved crop-water relations, but yields are reduced in wet environments due to other constraints, such as disease.

Kirkegaard (1995) fitted linear relationships using time (duration of experiment - years) and various measures of rainfall. At only one site (Tarlee, SA) was there a significant relationship between yield difference and time, and this was in only one rotation of eight used at the site (lupin/wheat, conventional cultivation; Ydiff = 0.1 (years) - 0.451; $r^2 = 0.57$). This increase in yield with stubble incorporation compared with stubble burning was attributed to the increase in soil organic matter during the experiment (Schultz, 1995).

There were significant relationships between Ydiff and rainfall at two sites (Wagga Wagga, NSW and Billa Billa, Queensland) where increasing rainfall reduced Ydiff (i.e. stubble retention lowered yield compared with stubble burning or removal in wetter seasons), as shown in Figure 27. At Wagga Wagga these relationships were between growing season rainfall, spring rainfall and total annual rainfall in the lupin/wheat rotation with direct drilling, and between growing season rainfall and total annual rainfall for the same rotation with reduced cultivation (one cultivation before sowing). At Billa Billa, significant relationships were for total rainfall (including preceding November and December rainfall) with Ydiff in a wheat/wheat system with direct drilling and for winter rainfall with Ydiff with wheat/wheat and conventional cultivation. At Billa Billa, increasing winter rainfall meant the loss of a potentially large yield advantage for stubble-retained crops (Figure 27). In dryer seasons at Wagga Wagga, there was no difference between stubble retention and stubble burning, but this changed to a yield disadvantage in stubble-retained crops as rainfall increased. The threshold appeared to be about 250 mm of growing season rainfall (Kirkegaard, 1995). The fitted threshold value in Figure 27 was nearer to 300 mm. This effect of growing season rainfall on Ydiff needs to be investigated as yield reductions with stubble retention were high (up to about 1 t/ha of grain) in seasons of high yield potential.

Table 23. Site information and the mean and range for yield difference between wheat crops for stubble retained (SR) minus stubble burnt (SB)/removed (SRem) systems, from medium-term and long-term experimental sites throughout Australia.

Site	Soil	Years	Sequence[1]	Tillage[2]	Stubble comparison	Yield difference (t/ha)		Reference
						Mean (± se)	Range	
Southern New South Wales								
4. Wagga Wagga	Red earth	1979-90	L/W	DDC[3]	SR *v* SB	-0.31 (0.11)	-1.08 to +0.24	(Heenan et al., 1994)
				C1	SR *v* SB	-0.35 (0.14)	-1.70 to +0.35	(Heenan et al., 1994)
6. Lockhart	Red-brown earth	1981-83	WW	DDN	SR *v* SB	-0.21 (0.12)	-0.36 to +0.03	(Mason and Fischer, 1986)
7. Yanco	Red-brown earth	1982-84	WW	DDN	SR *v* SB	-0.29 (0.05)	-0.70 to -0.40	(Fischer et al., 1988)
8. Harden	Red earth	1990-94	OWLWCW	DDN	SR *v* SB	-0.45 (0.18)	-0.80 to -0.24	Kirkegaard et al. (1994, unpublished)
				C1	SR *v* SB	-0.22 (0.30)	-0.74 to +0.30	Kirkegaard et al. (1994, unpublished)
Regional mean						**-0.30 (0.04)**		
Victoria								
11. Rutherglen	Red-brown earth	1981-92	WW	DDS	SR *v* SB	-0.12 (0.15)	-0.65 to +0.90	Steed et al. (1994, unpublished)
28. Rutherglen	Red-brown earth	1984-92	LW	DDS	SR *v* SB	-0.10 (0.21)	-0.53 to +0.48	Steed et al. (1994, unpublished)
29. Rutherglen	Red-brown earth	1985-93	LW	DDS	SR *v* SB	0.03 (0.41)	-0.72 to +1.60	Steed et al. (1994, unpublished)
30. Rutherglen	Red-brown earth	1987-94	LW	DDS	SR *v* SB	0.11 (0.23)	-0.34 to +0.45	Steed et al. (1994, unpublished)
Regional mean						**-0.02 (0.05)**		
Western Australia								
14. Merredin	Red-brown earth	1982-93	WW	DDC	SR *v* SB	-0.01 (0.05)	-0.14 to +0.14	Jarvis (unpublished)
				CC	SR *v* SB	0.04 (0.06)	-0.42 to +0.19	Jarvis (unpublished)
31. Merredin	Yellow earth	1979-94	WW	C1	SR *v* SB	-0.05 (0.03)	-0.19 to +0.26	Jarvis (1987, unpublished)
32. Wongan Hills	Earthy sand	1979-94	WW	C1	SR *v* SB	-0.32 (0.06)	-0.75 to -0.08	Jarvis (1987, unpublished)
Regional mean						**-0.09 (0.08)**		
South Australia								
33. Tarlee	Red-brown earth	1978-87	WW	CC	SR *v* SB	-0.14 (0.14)	-0.86 to +0.74	Schultz (1995, unpublished)
			LW	CC	SR *v* SB	0.10 (0.12)	-0.58 to +0.54	Schultz (1995, unpublished)

Table 23 (continued).

Site	Soil	Years	Sequence[1]	Tillage[2]	Stubble comparison	Yield difference (t/ha)		Reference
						Mean (± se)	Range	
					Queensland and northern New South Wales			
19. Hermitage	Black earth	1960-87	WW	DD	SR *v* SB	0.02 (0.09)	-0.51 to+0.81	(Marley and Littler, 1989; Thompson, 1989)
				CC	SR *v* SB	-0.04 (0.06)	-0.32 to +0.52	(Marley and Littler, 1989; Thompson, 1989)
20. Billa Billa	Sodic duplex	1984-93	WW	DD	SR *v* SRem	0.23 (0.19)	-0.94 to +1.08	(Radford et al., 1992; Thomas et al., 1995)
				CC	SR *v* SRem	-0.03 (0.07)	-0.42 to +0.30	(Radford et al., 1992; Thomas et al., 1995)
23. Breeza	Black earth	1983-89	WW		SR *v* SB	-0.04 (0.15)	-1.04 to +0.08	(Felton et al., 1993, 1995)
24. Croppa Creek	Grey clay	1983-90	WW	CC	SR *v* SB	-0.31 (0.12)	-1.12 to +0.01	(Felton et al., 1993, 1995)
25. Winton	Brown solodic	1983-90	WW	CC	SR *v* SB	-0.40 (0.11)	-0.96 to -0.11	(Felton et al., 1993, 1995)
Regional mean						**-0.14 (0.09)**		
Overall mean						**-0.15 (0.06)**		

Source: Kirkegaard (1995), reprinted with permission[36].

[1] W = wheat, 0 = oats, L = lupin, C = canola, SB = stubble burnt, SR = stubble retained, SRem = stubble removed

[2] DD = direct drill, DDC = full combine, DDA = combine sowing tines only, DDN = narrow points, CC = conventional cultivation (2-4 pre-sowing cultivations), C1 = one pre-sowing cultivation).

[3] Sowing points changed during experiment (see full paper).

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[36] ©CSIRO Publishing, Collingwood Vic (1995), 2 Oct 2009

The average, small yield losses with stubble retention in Queensland can be further examined. In the final 4 years of a 10 year experiment at Biloela, Queensland increased fertiliser (N, S and Zn) resulted in increased yield in the stubble-retained systems (Radford et al., 1995). These systems had greater soil moisture storage, but this greater yield potential was not realised until a fertility constraint was removed. At the Hermitage site, no-tillage and stubble retention increased the amount of soil water stored (Thompson et al., 1995). However, wheat responses to the extra water were disappointing in the first 11 years of the experiment, which was found to be caused by a population of a root-lesion nematode (*Pratylenchus thornei*). The plots were then split for wheat, and for barley, which tolerated the nematode. Barley responded to the increased soil moisture stored under the no-till, stubble-retained system and wheat responded to a nematicide. Thompson et al. (1995) concluded that full yield benefits to wheat from improved tillage practices required control of the nematode. These were examples of the recognition of constraints within a no-till, stubble-retained system, which could be managed to improve yield; these effects may not be fully accounted for in the conclusions of Kirkegaard (1995).

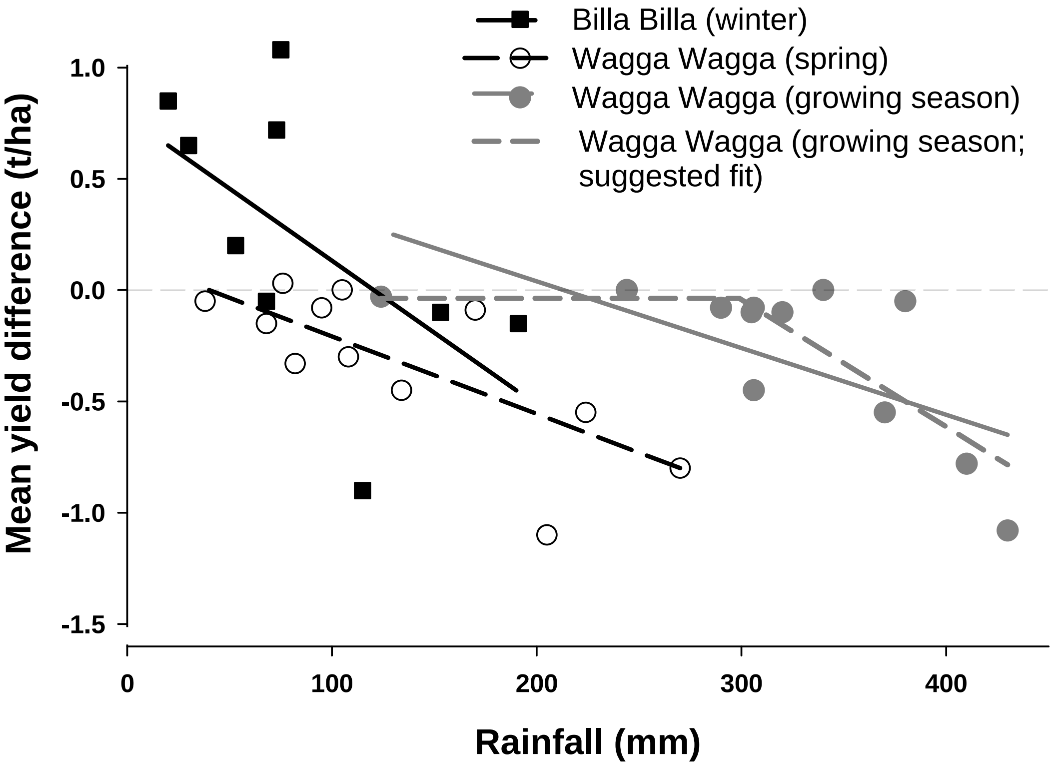

Figure 27. Relationship between rainfall (mm) and the mean difference in yield between stubble-retained and stubble-burnt/removed wheat crops in two long-term experiments at Billa Billa, Queensland in winter and at Wagga Wagga, NSW in spring or at Wagga Wagga over the spring/winter growing season from May-October. Source: Kirkegaard (1995), reprinted with permission[37]. An additional fitted line (light long dash) to the Wagga Wagga spring/winter growing season is also shown.

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[37] ©CSIRO Publishing, Collingwood Vic (1995), 2 Oct 2009

5. GENERAL AND CONCLUDING COMMENTS

5.1 Extrapolating from Long-term Experiments to Commercial Agriculture

The results of long-term experiments do not always predict the outcomes in commercial agriculture. Limitations are imposed on long-term experiments which are not important or not relevant to farming. This has a number of implications for the transfer of the data obtained to commercial agriculture.

Experiments comparing stubble burning and stubble retention may be sown on the same day to preserve the comparison. However, if stubble retention maintains surface soil moisture at higher levels than stubble burning then the option to sow earlier with stubble retention would arise. Similarly, any retention of moisture could extend the sowing window in a way useful to farmers sowing large commercial areas, but would be less relevant in experimental sowings. Also, if the rotations and cropping sequences in long-term experiments were set , this could lead to apparently poor agronomic practices. For example, in lupin wheat rotations, lupin would be late sown if necessary to execute the experiment, but this would not be undertaken by a commercial farmer who would consider a change to peas or barley for a late sowing. Weed control in long-term experiments could include repeated spraying of plots and even hand weeding where these would not be realistic in agriculture.

Continuous cropping was used in long-term experiments at both Condobolin (Fettell and Gill, 1995) and at Wagga Wagga, NSW (Heenan et al., 1994). This applied to all except the wheat/subterranean clover treatments at Wagga Wagga. However, farmers in these areas would normally rotate the crop and pasture phase. Typical rotations are shown in Table 25.

Table 23. Some rotations used by farmers on the south west slopes of NSW.

	Year							
Rotation[1]	1	2	3	4	5	6	7	8
1	P	P	P	C	W	L	W	B/P
2	P	P	P	W	L	W/P	-	-
3	P	P	C	W	L	W/P	-	-
4	P	P	P	P	C	W	L	W
5	P	P	P	O	W	L	W	P
6	W	L	W	L	W	L	W	L

Source: Cregan (1991), with permission[38].

[1] P = pastures, W = wheat, B = barley, C = canola, L = lupins, B/P = barley undersown with pasture.

The "conventional cultivation", with three cultivations before sowing used in the Condobolin and Wagga experiments, is no longer current practice. About 80% of the crop in southern NSW was sown with nil or one cultivation prior to sowing (Davis, 2006) and any use of multiple cultivations is likely to occur in the transition from a pasture phase into a crop phase. The use of multiple cultivations continuously for 20 or 27 years (as at the Condobolin and Wagga Wagga experiments) is not represented in current agriculture.

The burning frequency (stubble was burnt every year, including lupin stubbles) in the Condobolin and Wagga Wagga experiments is also atypical. Burn frequency would be limited to stubbles of wheat and some barley crops where the stubble load was too great to reliably

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[38] ©Sydney University Press (1990), 30 Sep 2009

sow through (for example, greater than 2.5 t/ha). In practice this would mean that wheat stubbles not followed by pasture would be the main candidates for burning. Extrapolating from Table 25, 50% (W/L) to 16 or 25% of stubbles may be candidates for stubble burning. Stubble amount present at sowing was estimated from stubble amount post harvest (from grain yields, after Perry, 1992) and deducting 1 t/ha as stubble loss/decomposition over summer/autumn. At Condobolin 50% of wheaten stubbles were < 2.5 t/ha, while at Wagga 22% were < 2.5 t/ha. The estimated frequencies of burns in commercial agriculture would be between 8 and 25% of years at Condobolin, and 12 to 39% at Wagga wagga depending on rotation and season. In both experiments continuous cropping was emphasised, and the cultivation and stubble burning treatments imposed were unrealistically frequent.

Researchers were obliged to manage considerable amounts of stubble on some occasions to maintain their experiments. In the extreme this has involved raking the stubble off the plot before sowing, and then raking the stubble back onto the plot. By comparison the stubble amounts experienced by farmers may be much less as many would burn heavy stubble. However, the promotion and adoption of sowing machinery capable of handling large amount of stubble would move farmer experience closer to that experienced in the long-term experiments.

Finally the practice of widening crop row spacing to assist with stubble handling may have biasing the grain yield results of some experiments. Using wide rows spacings in experiments to improve stubble handling probably imposed a yield penalty on the stubble burnt/removed treatment where this widening of rows was unnecessary. At Condobolin 210 mm row spacing was used and 180 mm at Wagga Wagga

5.2 Future Research Needs

Progress in adoption of stubble retention in central and southern NSW may require a new approach. The primary sources of benefit from the practice need to be identified and constraints to achieving that benefit need to be removed. These appear to be clearer in some regions than others.

In Queensland, erosion control (Freebairn and Silburn, 2004; Loch and Donnollan, 1988) and increased soil moisture storage (Marley and Littler, 1989; Radford et al., 1992; Thomas et al., 1995) drove stubble retention. Retained stubble has only a small negative impact, or no impact, on grain yield (Kirkegaard, 1995) and some positive responses were reported (Radford et al., 1995; Thompson et al., 1995). In WA, potential wind erosion was a motivating force (Findlater et al., 1990; Findlater and Riethmuller, 2000). Notably, stubble loads at sowing in both states were relatively low due to low grain yield in WA, and the rapid breakdown of stubble over a wet summer in Queensland. These stubbles were able to be managed using modified machinery. In contrast, in much of south-eastern Australia, while stubble retention was claimed to have many benefits, none stand out. Most of the wheat belt of central and southern NSW (all except the eastern edge of the central west and south west cropping zone) is flat (1-2% slope), so less prone to water erosion. Wind erosion has occurred predominantly in dry seasons. A case for stubble retention is therefore more difficult to mount. In addition, the practice of late stubble burning in the southern states has many of the characteristics of a stubble-retained system, as soil was protected over summer from intense rainfall and infiltration of moisture was maximised.

There appear to be increased risk of significant yield loss in seasons of higher rainfall (see Figure 27). Yet, it was in such seasons that farmers depend on achieving good yields to compensate for ‘lean’ seasons. Further, stubble loads can frequently be substantial, particularly in the eastern areas of southern and central NSW. Stubble-retained systems also appeared to require greater management input than the systems they replaced. Disease carry over on stubble make sequential wheat crops a greater risk and rotations and cropping sequencing more challenging. Stubble retention has probably contributed to the development of herbicide resistance in conservation farming systems. The weed control achieved by burning was absent from the system and this made it more dependent on herbicide use, particularly for grass weed control. The potential importance of earthworms may also limit the range of insecticides able to be used in the stubble-retained system.

However, the practice of burning stubbles may be banned in the future. Advances in machinery capable of seeding into heavy stubble loads are well-advanced, as are several stubble management options to assist in reduction of stubble load or passage of machinery. Thus, it would be prudent for agricultural research to identify and address the problems of crop production related to stubble retention, specifically surface retention of stubble.

There would appear to be an option of breeding a wheat “adapted” to a stubble-retained system. One of the major constraints on yield in stubble-retained systems was disease. While some agronomic practices can assist (e.g. rotational sequence, row placement and sowing depth) plant breeding offers a major approach. Sources of disease resistance have been identified and applied breeding is required. However, solutions via plant breeding are likely to eventuate in the longer, rather than short-term. Similarly, problems with plant establishment under stubble may be addressed genetically through long coleoptile wheats that minimise the consequences of poor depth control at sowing and assist emergence through stubble. Equally, the competitive ability of wheat and incorporation of specific allelopathic characteristics into new cereal cultivars may be possible in the future.

Innovations in herbicide technology, more suited to surface stubble retention, are progressing and ultimately may allow greater variation in herbicide use to combat development of herbicide resistance that is presently an adverse outcome of stubble retention/zero-till systems. Adjustment to nutrient management in stubble-retained systems has already been quantified in some regions for some nutrients, particularly nitrogen. However, further work will be required. Above all, farmers will resist change unless solutions at least sustain production and prevent loss in yield, relative to nil stubble farming in high rainfall seasons. These issues should be the research foci for the future.

Some problems may develop in stubble-retained systems that require occasional application of ‘non-conservation’ practices, such as stubble burning and/or cultivation. These may include managing herbicide resistant weeds, limiting disease carry over, redistributing stratified nutrients, and incorporating lime into acidified soils. The occasional use of burning and cultivation in systems otherwise maintained with direct drilling/no-till and stubble retention has not been adequately investigated. This goes to the heart of the primary drivers of benefit of stubble-retained systems. If conservational systems accrue their benefits over many years of maintenance of ‘the system’ then it could be assumed that tillage and burning would lead to ‘resetting the clock to zero’. If the benefits of conservational tillage accrue rapidly, then disruption by occasional cultivation or stubble burning may be overcome rapidly upon returning to conservational farming.

5.3 Who Benefits from Adoption of Stubble Retention Systems?

The suggestion that farmers should adopt stubble-retained systems implies that they meet any costs and, reap any benefits, of this adoption. The assumption is that there is a net benefit to farmers, or they will not take up the practice. However, as presented in the current monograph, using current technology, the effects on grain yield of stubble retention are largely negative. The farmer adopting stubble retention is meeting additional costs (machinery modification or purchase, and potentially increased field operation to roll/slash/harrow stubble and probably increased application of pesticides and nutrients) and may not be receiving an economic benefit via grain yield. Soil surface condition was shown to improve under stubble retention, which may provide benefit to the farmer.

The benefits of the change in practice may possibly accrue to the community in general. Adoption of stubble retention may reduce smoke pollution, and turbidity and nutrient concentrations in waterways. Increased sequestering of C has appeal, if farmers were to be paid for this, but it appears unlikely that sequestering will be achieved in cereal cropping areas.

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