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The impact of tillage practices and crop residue (stubble) retention in the cropping system of Western Australia

Geoff Anderson

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3 Baron-Hay Court, South Perth WA 6151
Tel: (08) 9368 3333
Email: enquiries@agric.wa.gov.au
www.agric.wa.gov.au

Contents

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The project is a development of the workshop titled 'Issues and Practices relating to Stubble Management' held at the Department of Agriculture and Food, Centre for Cropping Systems, in Northam during December 2004. The workshop was organised by Peter King, formerly Regional Director of the Central Agricultural Region. Contributions to the workshop were made by Mike Collins, Lisa Sheriff, Bill Bowden, Blakely Paynter, Ian Pritchard, Darshan Sharma, Harmonhinder Dhammu, David Minkey, Abul Hashem, David Ferris, Sam Giles, Kathryn Egerton-Warburton, Roy Butler, Chris Gazey, Linda Leonard, Jeff Russell, Erin Wright, Wendy Dymond and Cherie Trinder. The ideas presented at the workshop form the basis of this bulletin.

1. Summary

This review examines how soil erosion by water and wind can be controlled by maintaining soil cover using the conservation farming practice of no-tillage with stubble retention. A form of this practice is currently used by most farmers in the Western Australian wheatbelt. However, some situations can arise which make it difficult to manage stubble levels. Hence, this review examines the various options available to farmers to manage their stubble levels in relation to their tillage and harvesting systems. It also examines the impact of various stubble retention and tillage practices have on soil carbon and greenhouse gas emissions, soil fertility and fertiliser efficiency, soil acidity and lime effectiveness, herbicide behaviour and effectiveness and the occurrence of diseases.

Stubble management practices are directed at modifying crop stubble levels to reduce clumping problems at seeding. Stubble management begins at harvest by setting the cutting height of the header and the spread pattern of the stubbles which will enable the seeding bar to get through the stubble. However, farmers will often minimise the management of stubbles at harvest due to the higher cost of running the header and the reduced speed of harvest. In these situations post harvest management options to reduce stubble levels are necessary. Seeding bar design and set-up can both result in reduced clumping and blockages at seeding. A tramline farming system enables inter-row or on-row sowing. This has the potential to reduce clumping, improve crop establishment and reduce the impact of nitrogen immobilisation and diseases. It also offers opportunities to reduce the impact of wind and water erosion that are not available with other conventional techniques.

Research on the carbon cycle in cropping systems has changed over the past decades. This review illustrates how research was directed at first to examining how to prevent soil carbon decline following cultivation, then concentrated on developing reduced tillage and stubble retention systems that could maintain soil carbon content. Recently the problem of greenhouse gas emissions (carbon dioxide and nitrous oxide) from the agricultural sector has renewed interest in studying the benefits of conservation farming practice on greenhouse gas emissions.

Soil acidification is a natural process that is accelerated by agriculture. Lime application is the main practice for correcting soil acidity, currently applied to the soil surface in a cropping system where the main cultivation practice is no-tillage. Under this system, lime responses can take a number of years to develop due to the slow rate of dissolution and leaching of surface applied lime. Given the widespread occurrence of both surface and subsoil acidity the review illustrates how there is a need to obtain a better understanding of lime dissolution and movement for the correction of surface and subsurface acidity in no-tillage systems.

Herbicide behaviour in the environment is determined by various soil processes, including sorption, volatilisation, degradation and plant uptake. Sorption and degradation are perhaps the most important, but the relative importance varies with environmental conditions and herbicide properties. Trifluralin is used as a pre-emergence herbicide and is one of the most commonly used herbicides in southern Australia. Stubble is thought to reduce trifluralin efficiency by interception and sorption of the applied trifluralin. The review highlights the difficulty in conducting research into herbicide efficiency where stubble management practices have an impact on weed control.

2. Introduction

Initially, the aim of this review was to outline issues and practices associated with stubble management. However, as work progressed it became clear that tillage is closely linked to stubble management. Hence, the focus is now on the costs and benefits of conservation farming—that is, the use of minimum tillage with stubble retention. Continuous cropping systems place a great deal of pressure on the soil resource and careful management is required to maintain sustainability. Cropping system failure is most dramatically highlighted by extreme weather events, for example, the occurrence of drought conditions in 2006 and 2007 in the Northern Agricultural Region. There are also many examples of less extreme cropping system failure that are developing slowly and having a much less visual impact, for instance soil carbon decline, nutrient removal, soil acidification and herbicide resistance.

Lynam and Herdt (1989) define sustainability as the capacity of a system to maintain output at a level approximately equal to or greater than its historical average, with the approximation determined by its historical level of variability. Hence a sustainable system is one with a positive trend in measured output and a technology enhances it if it increases the slope of this trend line. A problem with this definition is that it focuses on the productivity of an individual system at the expense of other systems, including the environment. Nevertheless, it provides a framework by which the sustainability of a system can be analysed. No-tillage combined with stubble retention is seen as the way to maintain long-term sustainability in terms of soil conservation in the cropping systems in Western Australia. Adoption of new technology and farming practices is seen as the key to improving the sustainability of the system.

Conservation farming involves the farmer making decisions on harvesting practices, grazing management and seeding machinery set-up that impact on the potential for wind and water soil erosion (Gebhardt et al. 1985). No-tillage is a fairly recent practice, with only 15 per cent of WA adopters reporting any tillage use before 1994. However most wheatbelt farmers are using no-tillage or minimum tillage practices with stubble retention for at least a proportion of their cropping programs (D'Emden and Llewellyn 2006; D'Emden et al. 2009).

The main reason farmers adopt conservation farming is for soil conservation. Tillage and stubble practices have the potential to impact on a range of physical, chemical and biological properties of soil. This includes impacts on soil carbon (SOC) and nutrient availability, addressing the concentration of soil carbon and nutrients on the soil surface where they are at risk of been lost to wind and water erosion and the prevention of soil structural decline (Hamblin 1987). Other common reasons for adopting conservation farming were improved sowing timeliness, enhanced moisture conservation, reduced production costs (Al-Kaisi and Yin, 2004), and decreased consumption of fossil fuels (Phillips et al. 1980).

Main reasons given for not adopting conservation farming include machinery costs, reduced weed control options and increased root disease (Cook and Haglund 1991); the release of phytotoxins from the stubble resulting in poor crop establishment; adverse effects on input efficiencies of fertilisers, lime, herbicides and fungicides and increased insect and slug damage. Other factors which impact on the ability of farmers to retain crop stubble have been reported, particularly in the Mediterranean climate of the wheatbelt of southern Australia where the lack of summer rainfall results in low rates of stubble decomposition. Also, cereal stubble levels have increased over the past decade due to higher crop yields and shorter crop rotations, resulting in increased problems during the sowing.

Herbicide resistance and weed control issues are the main reasons some adopters are reducing their use of minimal tillage (D'Emden and Llewellyn 2006). Most growers who adopt minimal tillage do so with an awareness of the greater herbicide resistance risks compared

with tillage-based systems. Therefore, just raising basic awareness of the herbicide resistance risks in minimal tillage systems or promoting tillage for weed control will not have an extensive impact. The challenge is to develop and extend sustainable weed management strategies that are compatible with minimal tillage systems if both soil conservation benefits and weed management sustainability are to be maximised.

Given the complexities of farming systems, it is unlikely that one ideal system exists that will be suitable to all soils, environmental conditions and financial positions of individual farmers. Farmers are constantly changing and developing their cropping systems to improve efficiency and overcome problems. They are also at varying stages in the adoption of new technologies and farming practices such as precision agriculture and tramline farming. Often a change will solve some problems but could trigger other problems in the future. The issue is to identify these future problems before they start to impact on farm profitability.

Machinery issues of tillage and stubble management have been intensively examined in recent years. There are now machinery options available which, combined with management practices, can overcome the physical stubble handling problems at seeding. However, there is a need to better understand the impact of tillage and stubble retention on the chemical, biological and physical processes that determine the sustainability of the cropping system. The aim of this review is to highlight the underlying chemical, biological and physical processes related to cropping systems, to examine recent research conducted on these processes and to develop management solutions with the resulting benefits and future challenges for each solution.

3. Climate and soils

3.1 Region

The Southwest Agricultural Region is defined as the south-west corner of Western Australia (WA) that receives greater than 275 mm of annual average rainfall (Keen 2000). It is located in the middle latitudes (30–40 °S) and its climate is classified as temperate with dry summers (Trewartha 1943), commonly referred to as a Mediterranean type climate.

The dominant land use in areas that receive greater than 450 mm annual average rainfall is grazing (Keen 2000), while in areas that receive 300–450 mm annual average rainfall it is cropping. This division gives approximately 12 million ha where grazing is the dominant land use and 14 million ha where wheat cropping is the dominant land use—commonly referred to as the wheatbelt. However, fluctuations in commodity prices change the proportion of land grazed or cropped within these two areas (Poole et al. 2002).

This bulletin concentrates on issues related to continuous cropping systems of the wheatbelt region. The grazing of sheep and cattle occurs within the region and overgrazing can have a major impact on the soil resulting in erosion, however it is beyond the scope of this bulletin to include pasture and livestock grazing issues.

3.2 Weather patterns

Three climate characteristics are expressed strongly within the region and include:

- concentration of the rainfall in the winter with nearly or completely dry summers
- summers are warm to hot and winters mild
- solar radiation is high, especially in summer.

Weather conditions can have a strong impact on soil erosion (by wind and water). Severe winds and heavy rain can occur due to decayed tropical cyclones and cool season storms. Decayed tropical cyclones occur over the period November to May and cool season storms from April to November. Decayed tropical cyclones and cool season storms have the greatest potential to result in soil erosion where the ground cover is low due to grazing, burning or sowing (March to June).

3.2.1 Tropical cyclones

Tropical cyclones are intense lows which develop off the coast of north-west Australia and tend to cross the coastline between Broome and Exmouth. On average about five tropical cyclones occur each tropical cyclone season (November to April). Tropical cyclones decay, or weaken, as they move south and encounter cooler seawater. Those that cross the coast and weaken over land may continue to produce strong winds and heavy rain a considerable distance inland. Occasionally a cyclone moves south and interacts with a mid-latitude trough and undergoes extra-tropical transition, changing from a warm-cored tropical low to a cold-cored mid-latitude low. An example is illustrated in Figure 1 and Figure 2 where tropical cyclone Clare moved south to interact with a trough resulting in 231 mm of rainfall in 48 hours at Lake Grace on 11–12 January 2006.

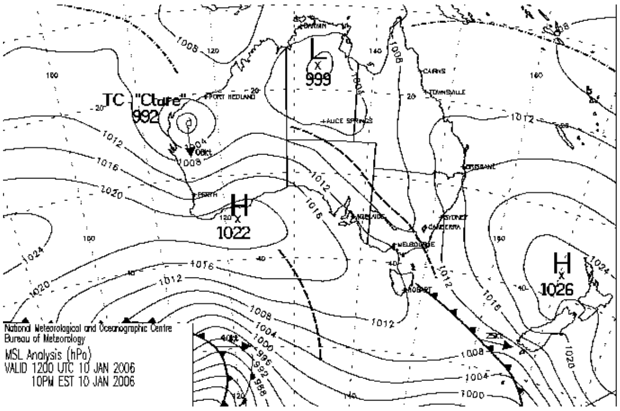

Figure 1 **Isobar map for 10 January 2006**

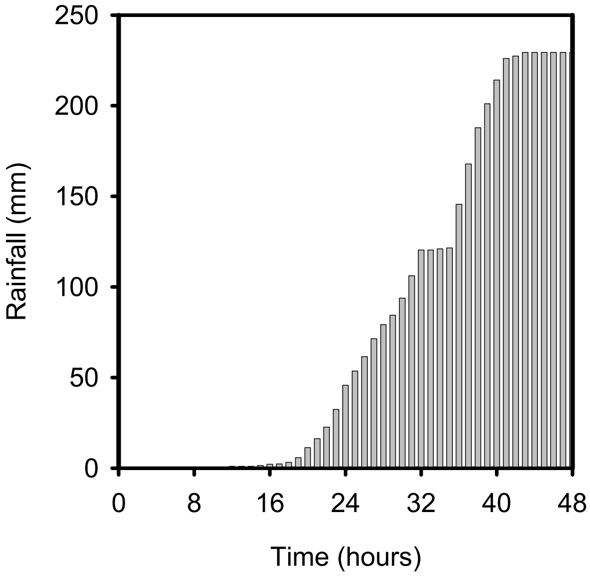

Figure 2 **Cumulative rainfall (mm) received at Lake Grace over 48 hour period, 12–13 January 2006**

3.2.2 Cool season storms

Cool season storms are strong fronts and intense lows that cause sustained gale-force winds and severe gusts over a large area. Cold fronts embedded in the westerly flow bring the rain and strong winds on an irregular cycle every few days during March–November. Each front is unique, varying with the strength of wind and amount and distribution of rainfall.

Only a few times each year do very strong cold fronts associated with deep low-pressure systems affect the region. A simple indicator of the intensity of fronts affecting the lower west coast is the pressure gradient from Geraldton to Albany. A 'storm event' can be said to occur when the pressure gradient exceeds 15 hPa. This threshold generally correlates to gale-force winds on the coast and wind gusts exceeding 90 km/h. There have been 100 such events over the 39 years from 1965 to 2003, equating to about 2.6 per year. Seventy per cent of these storms are distributed relatively evenly between the months of June and September, although they have been recorded as early as April and as late as November. An example of a cool season storm occurred on 9 May 2004 (Figure 3). It resulted in large visual soil erosion and was particularly severe because the strong winds, up to 70 km/h, occurred without any significant rainfall (Figure 4).

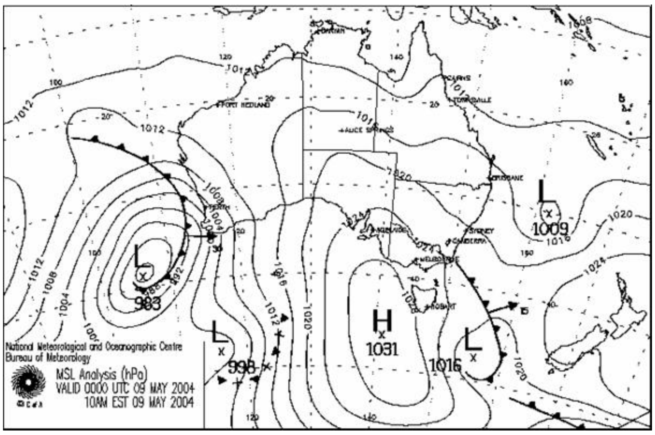

Figure 3 **Isobar map for 9 May 2004**

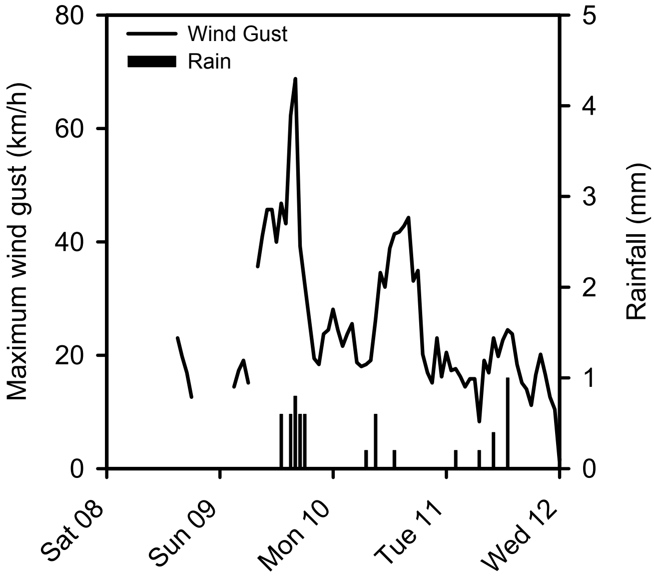

Figure 4 **Maximum wind gust speed (km/h) and rainfall (mm) 8–12 May 2004 measured at Wongan Hills Research Station**

3.3 Soils

The soils of the region are highly weathered and generally have coarse textured surfaces (Moore 2001). Schoknecht (2002) has developed a simple soil classification system (Soil Groups of WA) that uses common names and general soil morphology features (Figure 5). A more rigorous technical system for classifying Australian soil is given by Isbell (1996).

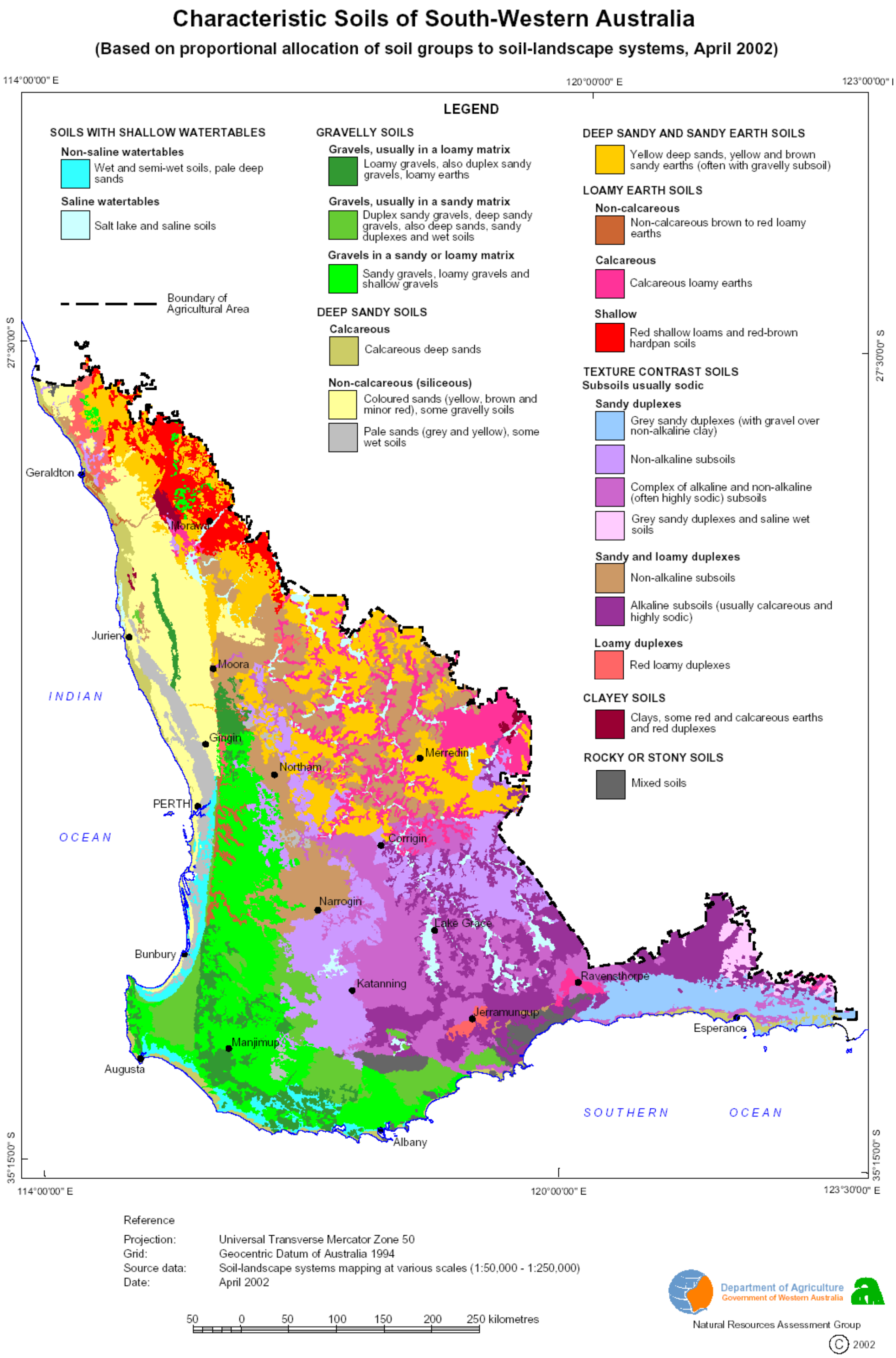

Figure 5 **Characteristic soils of the SW region of WA based on proportional allocation of soil groups to soil-landscape systems (Schoknecht 2002)**

The Soil Groups of WA system describes 13 super groups according to three primary criteria:

- surface texture and the change in texture with depth
- presence of coarse fragments (stone or ironstone gravels)
- water behaviour, for example waterlogging.

The area associated with each soil group is given in Table 1. Sandy or coarse texture soils cover 13.2 million ha (or 50 per cent of the landscape), loams cover 4.3 million ha (18 per cent) and ironstone gravels 3.9 million ha (15 per cent). Finally clays cover only 0.8 million ha or 3 per cent of the landscape.

All these soil groups are subject to wind and water erosion given certain conditions, however coarse texture soils and ironstone gravels (17.1 million ha) are particularly susceptible, especially when plant residues are removed by burning or overgrazing. Soil structural decline is mainly associated with loams and clays (5.1 million ha) when plant residues are removed and the soil is cultivated.

Table 1 **The thirteen soil groups of the SW region of WA: area and percentage of area (Schoknecht 2002)**

No.	Soil super group	Hectares	% of area
1	Wet or waterlogged soils	2 275 000	8.5
2	Rocky or stony soils	868 000	3.3
3	Ironstone gravelly soils	3 937 000	14.8
4	Sandy duplexes	6 574 000	24.7
5	Shallow sands	658 000	2.5
6	Deep sands	4 347 000	16.3
7	Sandy earths	1 640 000	6.2
8	Loamy duplexes	2 068 000	7.8
9	Shallow loams	758 000	2.8
10	Loamy earths	1 915 000	7.2
11	Cracking clays	302 000	1.1
12	Non-cracking clays	476 000	1.8
13	Miscellaneous soils	842 000	3.2
	Total	**26 660 000**	**100**

4. Soil erosion

Control over the processes of wind and water erosion in cropping systems is achieved by maintaining soil cover with stubble. Findlater (1989) observed that when 50 per cent of the soil surface is covered by stubble, wind erosion is reduced by 85 per cent. Slow initial plant crop growth means adequate ground cover needs to be maintained for 6–8 weeks following seeding (Leonard 1993). It is generally considered that 1 t/ha of cereal stubble or 2 t/ha of lupin stubble or 3 t/ha of canola stubble achieve 50 per cent ground cover. Standing stubble is more effective than flat stubble in preventing soil erosion.

4.1 Water erosion

4.1.1 Process

Soil erosion due to water run-off is also a major cause of soil degradation in the region (Coles and Moore 2001). Water run-off occurs by the processes of infiltration excess run-off and saturation excess run-off (Coles 1993).

- **Infiltration excess run-off** occurs when the rainfall intensity exceeds both the infiltration capacity of the soil and its surface storage capacity. It is normally associated with intense rainfall and/or soils that have slow rates of infiltration—fine texture soils with low infiltration capacities, surface sealed and hard setting soils, water repellent soils and surface compacted soils.
- **Saturation excess run-off** or saturated overland flow is generated when rain falling on saturated soils results in ponding and run-off. It is commonly associated with permeability contrast soils; under conditions where perennial groundwater rises to the surface; where groundwater is discharged; on fine texture soils on the valley floor; and on saturated ploughed soils.

The introduction of conservation farming practices of no-tillage and stubble retention has improved soil structural stability and internal drainage (Blackwell 2000). The net effect has been a reduction in the risk of run-off and soil erosion by infiltration excess run-off. This has lead to some farmers removing contour banks to improve access to the paddock for cropping. Nevertheless contour banks remain necessary on sloping sites (> 3 per cent) to safely divert large volumes of run-off from intense storms or after soil profiles becomes saturated during a wet winter.

Soil erosion due to run-off is an expensive exercise to measure in the field so it is best estimated by the use of models. The Revised Universal Soil Loss Equation version 2 (RUSLE2) predicts on-site soil degradation and off-site sediment yield (Dabney et al. 2006). It predicts average annual soil loss based on the product of five factors:

- Rainfall erosivity—the potential of the rainfall to cause erosion. It is a function of the physical characteristics of the rainfall drop size, velocity and intensity.
- Soil erodibility—related to soil characteristics such as surface storage capacity, infiltration rate, soil texture, aggregate stability.
- Slope length and steepness—the longer the slope and the greater its steepness the greater the potential for soil erosion.
- Crop management—vegetation cover and tillage practices.
    - Vegetation cover absorbs the energy of the falling raindrops thus reducing rainfall splash; surface plant material can retard overland flow, while plant root systems bind the soil together.

  - Tillage practices can increase surface roughness, loosen the topsoil, disrupt soil aggregates and compact the subsurface soil, thus increasing infiltration rates of the cultivation layer leading to saturation of the cultivation layer and increased soil erosion by saturation excess run-off.
- Supporting practices include contour tillage and strip cropping on the contour.

4.1.2 Management

Large summer rainfall events are common throughout much of the WA wheatbelt. Thus there is a need to ensure that farming practices protect the soil resources from water erosion. However many of the old contour banks covering the agricultural landscapes are falling into disrepair or being removed altogether by farmers wanting to manoeuvre more easily within paddocks (Blackwell et al. 2006). New precision agriculture tools such as tramline farming and auto steer offer opportunities not available with other techniques. Thus up and back practices are being adopted in place of round and round seeding of paddocks. Queensland research has shown that controlled traffic systems like working downhill on slopes of up to 2 per cent can reduce the incidence of gully erosion from intense storms compared to contour planting, provided there is good ground cover and water infiltration.

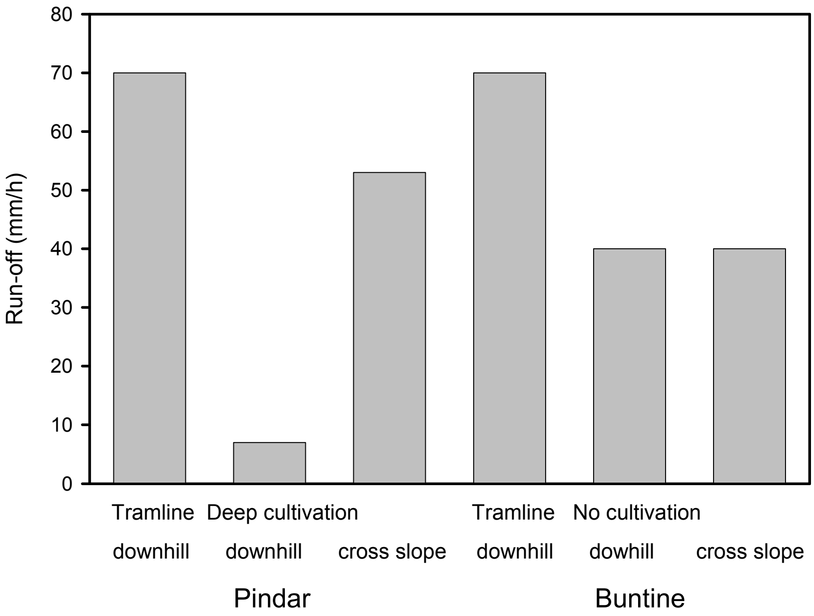

Figure 6 **Run-off from 100 mm/h simulated rainfall measured on gravelly sand with 5–10 per cent stubble cover at Pindar and Buntine with slopes of 1.5–3.0 per cent**

Water run-off was measured from a simulated 100 mm/h rainfall event in paddocks near Pindar and Buntine with stubble cover levels of 5–10 per cent in February 2006. The greatest run-off rate was from the tramlines in a downhill working system (slopes of 1.5–3.0 per cent), and the least run-off from a deep cultivated soil between the tramlines at Pindar, where the compaction had been removed (Figure 6). However, where the soil is compacted or ground cover levels are low (e.g. after grazing which loosens the soil surface) run-off from downhill systems can be greater than cross slope systems. Thus there remains a need for appropriate earthworks to control the rate of overland water flow and minimise the risk of soil erosion from intense rainfall events.

Broad-based channels provide a viable option to existing surface water management banks. They allow for increased cropping areas and sowing along the longest runs when converting to auto steer systems using tramline technologies. A broad-based channel has a broad, flat,

upslope channel constructed using a grader. It is designed to intercept run-off from sloping land and divert it into a grassed waterway or farm dam. The broad-based bank has a channel approximately 4 m wide compared to a conventional bank with a 1 m channel. The height of the bank is only about 300 mm from the channel floor but the channel has the same water volume capacity. Broad-based bank construction covers about 20 to 25 m but now the whole bank area can be sown to crop.

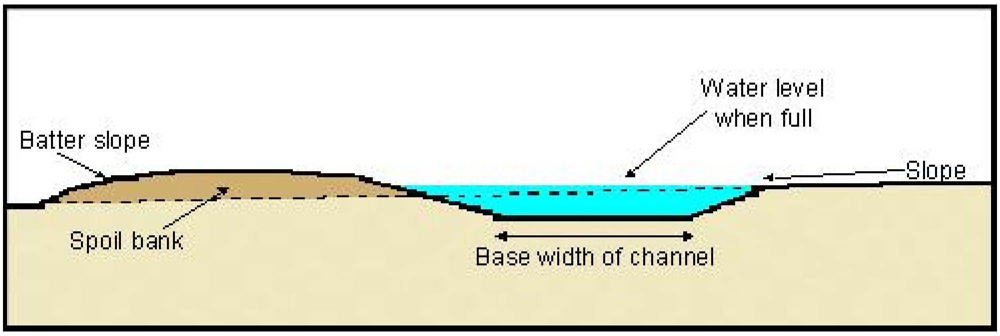

Figure 7 **Cross-section of a broad-based channel with low profile**

These structures are suitable for use on farmland in the lower and middle parts of the landscape on slopes ranging between 2 and 6 per cent. The broad, flat-bottomed channel, low spoil bank and gentle batters give the structures a smooth cross-section with a low profile that provides a large capacity channel (Figure 7). These channels are aesthetically pleasing, have a potential use for water harvesting, will decrease the extent of flooding and inundation in the lower landscape and reduce the potential for down-slope salinity and waterlogging. The low profile allows for stock, tillage equipment, farm machinery and vehicle passage across the length of the channel, enabling the area to be sown using current seeding practices (Figure 7) with control of weeds. These advantages are expected to overcome the higher construction cost of $1500 to $2000/km compared to standard banks which are priced at around $700/km.

Photograph 1 **Ross Fitzsimmons seeding across a broad-based channel (a) to obtain an established wheat crop (b)**

Broad-based channels are the perfect water management strategy for tramline farming (Webb et al. 2004). When developing tramline farming system it is important to make sure the layout of tramlines is compatible with the control and safe disposal of run-off. Consulting contour maps and understanding the water movement is important preparation for determining tramline layout and the appropriate control measures. Tramlines should not stop at a hilltop; they should run over at the top to reduce hilltop run-off being fed down a tramline. Identifying the areas prone to surface water risks (erosion, flooding, water logging, etc.) is an important element in considering appropriate management options. Different parts of the

landscape have different surface water management issues, thus classification of soil types and slope will help to pinpoint the different surface water risks and options within the landscape.

4.2 Wind erosion

4.2.1 Process

The movement of soil particles by wind occurs as a result of three processes (Greeley and Inversion 1985), as described in Figure 8.

- **Saltation** occurs at point A where surface shear exerted by the wind causes a sand grain to be lifted and carried downwind. A higher saltation trajectory is obtained at point B where the sand grain hits a large rock and rebounds to a higher level. At point C the sand grain strikes the surface and triggers other grains into saltation.
- **Suspension** occurs at point D where the sand grain strikes the surface and causes very fine particles to be lifted into the air and carried by turbulence in suspension.
- **Creep** occurs at point E where the sand grain strikes the surface and pushes larger particles a short distance downwind. These larger particles are too big to jump into the saltation layer.

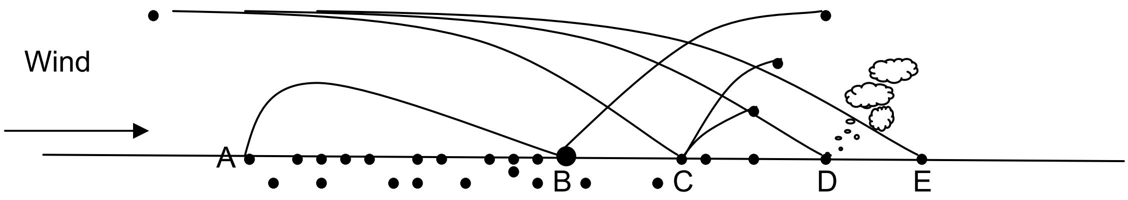

Figure 8 **The three processes associated with particle movement by wind**

The risk of soil erosion varies in space and time. It is dependent on the duration, turbulent structure and strength of winds; soil type; and the amount of anchored plant residue, soil moisture and crop cover (Moore et al. 2001b). The interaction between these factors and resulting dust and sand transport can be simulated with computer models. The Wind Erosion Assessment Model (WEAM) has been shown to provide realistic estimates of sediment transport on light soil types in southern Australia (Shao et al. 1996).

Wind erosion occurs when the velocity of the wind at the soil surface exceeds the threshold velocity required to move the least stable soil particle (Bagnold 1941). Once wind speed is greater than this velocity soil movement begins by the process of saltation. The detached particle may move a few millimetres before finding a more protected site, but when soil movement is sustained, the quantity of soil that can be transported by the wind varies as the cube of the velocity (Bagnold 1941). Soil roughness, erodibility and water content, along with the amount and orientation of stubbles, all impact on the vulnerability of soils to wind erosion (Fryrear 2000).

Wind erosion can reduce current season crop yields due to sandblasting and long-term crop productivity due to loss of soil nutrients. Environmental effects include atmospheric pollution that can adversely affect human health and visibility and impact on climatic conditions. Dust storms can impact on transportation due to reduced visibility and blowing soil onto roads, railroads and airports.

All soils are subject to wind erosion given certain conditions. The key factor is the level of disturbance (mechanical or animal) required to bring a soil to an erodible condition. The susceptibility of a soil can be assessed from a simple matrix of surface texture and surface condition. The five categories of wind erosion hazard in Table 2 relate to the level of disturbance needed to bring the soil to a loose and consequently erodible condition. The level of susceptibility to wind erosion decreases as the category level drops.

Table 2 **Rating of the susceptibility of bare soil to wind erosion from surface texture and surface condition (adapted from Moore et al. 2001b)**

Surface texture	Surface condition				
	Loose	Soft surface	Firm surface	Hard setting	Self-mulching
Fine–medium sand	5	4	3	–	–
Loamy sand–coarse sand	5	4	3	3	–
Sandy loam–light sandy clay	5	3	2	1	–
Clay loam–heavy clay	5	3	2	1	1–4

Note:

- Rating 1 is least susceptible to wind erosion; rating 5 is most susceptible.
- 20–50 per cent gravel or stone surface cover reduces the soil rating by 1; more than 50 per cent, it drops by 2.

Category 5 soils are highly susceptible because they have a loose surface and control must rely on the use of windbreaks and/or maintenance of adequate vegetative cover. Soils within categories 1–4 are less fragile and require some disturbance by machinery or stock to loosen the soil. Gravel physically protects the surface and increases roughness, thus reducing wind velocity at the soil surface.

Wind erosion is greatest when the soil surface is most erodible—smooth, bare, loose, dry and finely granulated (fine to coarse sands). Wind speeds as low as 18 km/h, 30 cm above the soil surface, are capable of starting soil movement under erodible conditions. Any erosion control system that reduces wind speed at the soil surface will reduce erosion. Small soil particles of 0.01 mm diameter are easily lifted from the soil and suspended in the airstream in a wind. Larger particles, 1 mm in diameter, are dislodged and propelled in a bouncing or jumping manner across the surface. Management practices should be aimed at reducing wind velocity at the soil surface (planting windbreaks), trapping soil particles (retaining stubble) and altering the surface condition by increasing the size of soil aggregates.

The position of soil groups in the landscape affects susceptibility to wind erosion, hence it is necessary to combine soil susceptibility (Table 2) with landform to obtain an overall landscape assessment. Landform influences wind speed and hence soil exposure to high winds.

4.2.2 Impact

Bennell et al. (2007) observes that sandblasting occurs when eroding soil particles strike plant surfaces. It results in tissue removal, which affects the physiological performance of the plant (Miller et al. 1995; Cleugh et al. 1998). The extent of injury to a plant species depends on wind speed and gustiness; abrasive flux; size, shape and density of the abrasive material; duration of exposure; and growth stage and condition of the plant (Skidmore 1966).

Lupins are one of the preferred legume species used in dryland crop rotations on shallow and deep sands that are prone to erode—more than 5 million hectares or 27 per cent of the SW agriculture region (Table 1). However, the probability of sandblasting damage is

increased if sown to lupins because of their slow growth and low vegetative cover during establishment.

Lupin meristems are above ground after seedling emergence and vulnerable to physical damage. Buds are easily damaged and the plants cannot recover by producing new shoots (Dracup and Kirby 1996). In contrast, cereals shoot apex remains underground during vegetative growth. Hence, lupins will suffer greater damage and subsequent yield depression than cereals when subject to an equivalent amount of sandblasting.

Bennell et al. (2007) reports the impact on the development and yield of narrow-leaf lupins exposed to different durations of sandblasting at a constant wind speed. A portable wind tunnel was placed in the field generating a turbulent boundary layer with a constant free stream mean velocity of 47 km/h. Lupins were then exposed to this velocity field with a total transport mass (TTM) of 0, 42, 78, 153, and 248 kg/m achieved by maintaining a constant rate of soil introduction and increasing the run time.

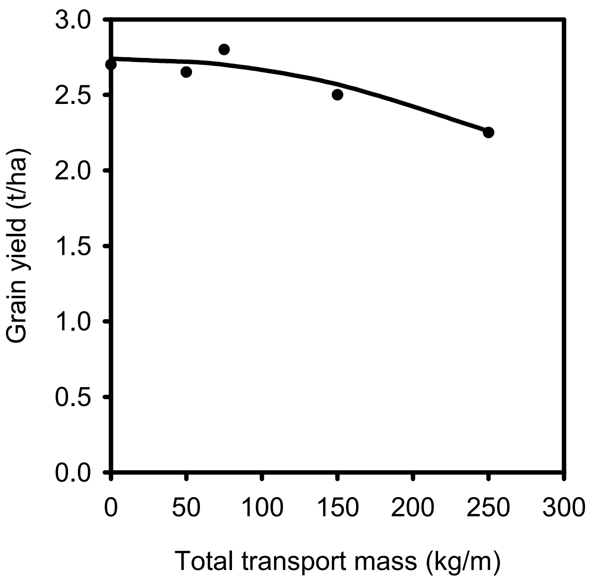

Figure 9 **Response of lupin yield (t/ha) to total transport mass (kg/m) observed by Bennell et al. (2007)**

Plants with an average leaf number of 3–10 showed increasing severity of damage with increased transport mass. The yield response of the lupin to total transport mass is shown in Figure 9. Lupins can suffer moderate levels of sandblasting at a total transport mass of 78 kg/m at 47 km/h wind speed with only negligible yield reductions (1 per cent). With this treatment, plants showed damage symptoms of wilting and burning of immature leaves and minor damage to mature leaves. Above total transport mass levels of 138 kg/m, yield losses greater than 5 per cent were measured. A yield loss of 18 per cent would be expected with a total transport mass of 248 kg/m when the plants were still immature with average leaf number to 10 (< 46 days after sowing). At this treatment level, damage symptoms included loss of most of the leaf tissue and scoring of the stem. The plants were able to recover from the meristem and continue growth but with a yield penalty.

For the soil type on which this crop was grown, sediment transport rate of this magnitude requires wind speeds of at least 47 km/h, as determined by the Wind Erosion Assessment Model (Shao et al. 1996). These results indicate that sandblasting can cause significant yield reductions in lupin and that measures to control soil erosion through minimum tillage practices with stubble retention or windbreaks are required.

Soil wind erosion occurs when the velocity of the wind at the soil surface exceeds the threshold velocity required to move the least stable soil particle by the processes of saltation, suspension and creep. The coarse texture sands of Western Australia are particularly prone to wind erosion. Lupins which have slow growth and low vegetative cover during establishment are the preferred legume species used in crop rotations on these soils. Hence, unless careful management practices are used for growing lupins sandblasting will occur. Also the lupin meristem is located above ground, making it vulnerable to physical damage. In contrast, cereals shoot apex remains underground during vegetative growth. Nevertheless, lupins can suffer moderate levels of sandblasting with only negligible yield reductions. But when exposed to high levels of sandblasting, yield loss can be as high as 18 per cent. It is recommended that conservation farming practices are used when growing lupins.

5. Management of stubbles

5.1 Introduction

Retention of crop stubbles is important for the prevention of soil erosion (wind and water). This can be achieved by growing cereal crops such as wheat and barley in rotation with annual legume pastures, grain legumes (lupins and field peas) or canola. In general the length and sequence of the rotation is variable and mainly driven by economic considerations. A common practice in recent years is to extend the cereal phase of the rotation, for instance two years of wheat followed by one year of barley then one year of a grain legume or canola. Thus it is common to sow a cereal crop into cereal stubble. In some situations where herbicide resistance has become a problem, paddocks are being fallowed for a year during which alternative weed management practice such as green or brown manuring are practiced.

A main concern of stubble management is determining the optimum stubble height to reduce clumping problems at seeding. Retained stubble can be cut high and left standing or cut low and either spread or windrowed, with windrow either burnt or baled. Stubble height can be reduced by slashing or mowing. The actual practice used is dependent upon the requirements of the subsequent crop in addition to traditional methodologies or practices.

Valzano et al. (2005) defined three stubble management practices:

- **Stubble retention** (SR) involves leaving stubbles on the soil surface, treated or untreated. The untreated stubble is considered standard harvesting by cutting high or low with no modification of stubble levels. The treated stubble is considered to have levels reduced by cutting low or by windrowing, baling or removal (chaff carts). This method of stubble management protects the soil surface from wind and water erosion, while retaining carbon at the soil surface.
- **Stubble incorporation** (SI) involves the use of tillage implements to incorporate remnant plant residue into the soil following harvesting. Traditionally this practice was considered useful in returning organic matter to the soil and protecting the soil from erosion. However, it can contribute to the transference of plant pathogens from one crop to another, offers less surface protection than other stubble retention practices, and can adversely affect soil structure and porosity.
- **Stubble burn** (SB) involves the burning of residues in autumn, a method commonly used in WA. Ideally, stubbles should be burnt just prior to sowing so as to minimise the time in which a soil is exposed to potential erosion.

Wheat stubble levels present in the northern wheatbelt after harvest of wheat crops ranged from 4.0 to 6.3 t/ha (Bhathal and Loughman 2001). These levels decline over time due to decomposition, with 1.8 to 4.7 t/ha remaining after establishment of first crop and 0.1–0.3 t/ha remaining after the second crop. Rates of stubble decomposition are determined mainly by:

- crop yield
- harvest index (HI), the ratio of crop yield to total biomass
- proportion removed between harvest to seeding
- proportion incorporated during seeding.

The amount of stubble present at harvest is calculated from grain yield measurements. This calculation is given in the following equation.

Equation 1 $$Amount\ of\ stubble\ (kg/ha) = \frac{Grain\ yield\ (kg/ha)}{Harvest\ index} - Grain\ yield\ (kg/ha)$$

The harvest index is generally considered to range between 0.2–0.5. It is determined by a large number of factors including seasonal conditions, crop variety, soil fertility, fertiliser and lime use, disease levels and weed competition.

Once potential stubble levels are estimated, farmers can undertake additional management practices at harvest, post harvest and seeding to reduce stubble levels to a level which results in no clumping problems at seeding.

5.2 Harvest

The cutting height of the header and the spread pattern of the stubbles are the main management options at harvest. Cutting height is important because it determines the resulting straw lengths of the stubble. When deciding cutter height it is important to know the height of the lowest obstruction under the seeding bar. The header should be set to cut the straw at a height which is 65 per cent of the total height of the lowest obstruction of the seeding bar. Standing wheat stubble is much easier to seed into than stubble that has been flattened by machinery. The use of tramline farming practices, and making any necessary wheel marks in the same direction as the rows, can minimise the effects of flattened stubble.

In weed free situations the stubble should ideally be spread evenly across the whole front width of the header. However, the spread is often uneven and spinners may be required to improve it. Most common spinners used to spread stubble have a power requirement of 1–2 kW (Collins and Lawson 2005). Second cutter bars fitted to a harvester can reduce the straw length at harvest, with the advantage that harvest speed can be maintained and straw can be spread evenly. The disadvantage is they can be easily damaged by rocks and can affect the warranty on new harvesters. Additional choppers and spreaders can be fitted to headers to improve stubble spread but these are expensive and increase the power use by 10–20 per cent of the harvester's total power.

Wheat stubble levels (t/ha) for various management treatments were measured at three sites located near the townships of Bruce Rock, Mukinbudin and Bonnie Rock in April 2005. Three stubble groups were obtained by sieving:

- Long stubble group—straw lengths of 10–20 cm for the cut low treatment, 20–30 cm for the cut high treatment and material that did not pass through a 4 mm sieve.
- Medium stubble group—straw lengths 2–10 cm and material that did not pass through a 2 mm size sieve.
- Short stubble group—straw lengths of less than 2 cm and material that did not pass through a 1 mm size sieve.

Wheat stubble levels were up to 6.6 t/ha at the Bruce Rock site and 4.3–4.7 t/ha at the Mukinbudin and Bonnie Rock sites (see Table 3). The higher amount of stubble at Bruce Rock was due to the retention of wheat stubble over two years. Windrowing of stubble reduced levels by 36–50 per cent at all sites and burning reduced levels by 81 per cent at Bruce Rock. Cutting stubble low reduced the long fraction by 26 per cent and increased medium and short fraction amounts at the Mukinbudin site.

Removed stubble can be included in Equation 1 by multiplying the amount of stubble by the proportion of stubble removed. It is important to use a value as proportion. That is, if 50 per cent of the stubble was removed by windrowing, the entered value is 0.50.

Table 3 **Wheat stubble levels (t/ha) for long, medium and short stubble groups measured at three sites in the central eastern wheatbelt**

Treatment	Wheat stubble group			Total
	Long	Medium	Short	
		Bruce Rock		
Cut low—windrowed	3.3	0.6	0.3	4.2
Cut low—burnt	0.5	0.5	0.3	1.3
Cut low—spread	4.2	1.8	0.6	6.6
		Mukinbudin		
Cut low—windrowed	1.3	0.6	0.4	2.3
Cut low—spread	2.4	1.4	0.9	4.7
Cut high—spread	3.0	0.8	0.5	4.3
		Bonnie Rock		
Cut low—windrowed	1.3	0.3	0.1	1.7
Cut low—spread	2.7	0.3	0.1	3.0
Cut high—spread	2.7	0.5	0.2	3.4

Harvest costs are increased when the cutting height is reduced because of the greater time required to harvest the crop. Increased harvest cost is also reflected in fuel consumption and header depreciation rate. Lower comb height reduces the evenness of the spread of the stubble and increases the risk of header damage from rocks, stones and sticks. Nevertheless, there are other benefits of cutting low in terms of collecting weed seeds which reduces the weed seed bank if the stubble is windrowed or removed using chaff carts, balers or burning of the windrow.

5.2.1 Fuel consumption

Green (1994) observed fuel consumption (L/ha) and header work rate (ha/h) to be predicted from header (comb height, engine power, and header drum type) and wheat crop characteristics (crop yield, crop height and crop variety). Although wheat varieties have changed with the introduction of dwarf varieties like Wyalkatchem and header size has increased from 130 kW to 230–280 kW, the principles observed in Green's work still apply.

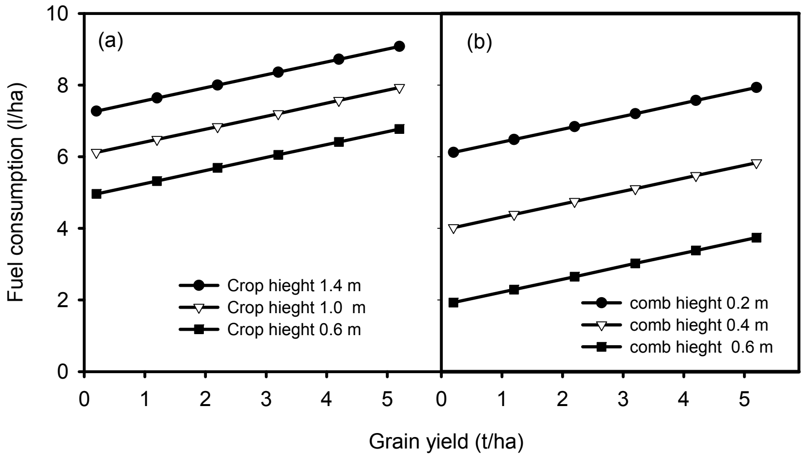

Figure 10 **Effect of grain yield (t/ha) on header fuel consumption (L/ha) with variations in crop and comb height**

(a) crop height (0.6 ■, 1.0 ▽ and 1.4 ● m) when comb height was set at 0.2 m and (b) comb height (0.2 ●, 0.4 ▽ and 0.6 ■ m) when crop height was 1.0 m. Data was obtained using a 130 kW engine power header.

In the same crop a conventional header used 2.1 L/ha less fuel than a rotary header, while increasing engine power by 30 kW increased fuel use by 1.2 L/ha (Figure 10). An increase in crop height of 0.4 m resulted in increased fuel consumption of 1.2 L/ha when cut height was set at 0.2 m. Similarly, an increase in comb height of 0.2 m resulted in a decreased fuel consumption of 2.1 L/ha for a crop height of 1.0 m.

5.2.2 Depreciation

The cost of the header is often the largest single machinery item on a wheat farm. Cutting the straw low reduces the speed of harvesting operations, thus increasing the rate of depreciation on the header. Traditionally, crop enterprise gross margins do not include a depreciation cost because it has been difficult to apportion between use depreciation (a variable cost) and time depreciation (a fixed cost) (Tozer 2004). In most farm operations depreciation is assumed to be a fixed cost, since the major component of depreciation is the age of the capital item and use does not significantly affect its value. However, when using the header to overcome stubble problems the variable cost component of the depreciation calculation becomes important.

Table 4 **Comparison of header depreciation rates ($/yr) when run at 5, 10 or 15 km/h over 3500 ha**

	5 km/h	10 km/h	15 km/h
Initial cost	$450 000	$450 000	$450 000
Age (yrs)	0	0	0
Expected life (yrs)	8	8	8
Annual usage (hrs)	497	398	265
Front width (m)	11	11	11
Harvest efficiency (%)	80	80	80
Harvest rate (ha/h)	4.40	8.8	13.2
Harvest cost ($/ha)*	57	28	19
Depreciation:			
Age value ($/yr)	26 650	26 650	26 650
Use value ($/yr)	10 739	5 369	3 580
Total depreciation ($/yr)	37 388	32 019	30 229
Total depreciation ($/ha)	10.7	9.1	8.3

* Running cost of a header assumed to be $250/ha

Basic information to estimate the depreciation cost for a header is easily accessible. It includes; initial header cost, age, expected life, front width, harvest speed and harvest efficiency. Harvest efficiency refers to the proportion of time spent harvesting relative to total time of running the header. To account for all these variables a depreciation calculator has been developed (Tozer 2005). Table 4 shows the depreciation expected when a header is used at low speed (5 km/h), medium speed (10 km/h) and high speed (15 km/h). The example is for a farm with a cropping program of 3500 ha and a rotation of three cereal crops followed by a legume crop.

5.2.3 Weed management

A number of options are available to farmers for removing weed seed at harvest: stubble chutes, chaff carts and header balers. Of the three, stubble chutes appear to be the cheapest option, but header balers produce a product—stubble hay—which can be sold to generate income.

The advantage of a stubble chute is that it enables stubble to be concentrated in windrows at harvest. Stubble that would normally be spread over 9–11 m (header front width) is placed into windrows 0.4–0.6 m wide.

Two types of windrow are produced from headers: conventional and chaff top. The chaff top windrow is obtained by inverting the stubble. This results in the header chaff being placed on top of the straw material. The chaff can then be baled along with the straw material after harvest. In conventional windrows the chaff material is placed on the ground and is difficult to collect when baling the windrow.

The amount of stubble concentrated in the windrow will depend on a number of factors: crop yield, harvest index, comb height, crop height, windrow width and comb width. For example, a wheat crop with a grain yield of 2 t/ha, crop height of 1.0 m and a harvest index of 0.4 will have stubble levels of 3 t/ha. Setting the comb at 0.4 m will result in 60 per cent of the stubble being transferred to the windrow. With a windrow width of 0.6 m and header front of 11 m, the windrow will concentrate stubble at a level of 33 t/ha (3 t/ha x 0.6 x 11/0.6) while leaving a ground cover of 1.2 t/ha.

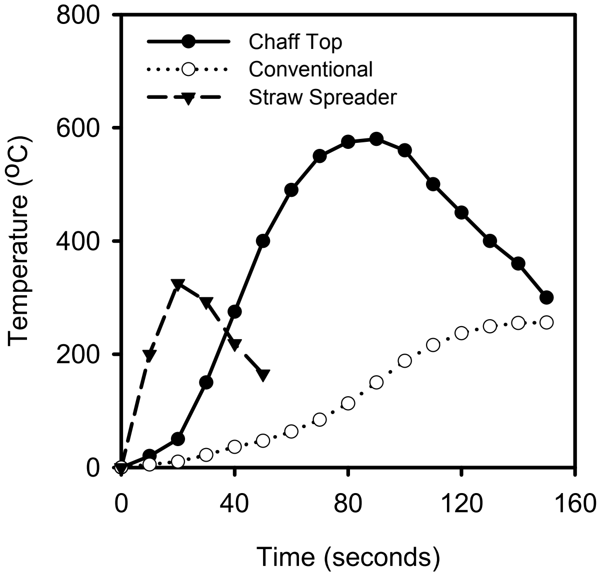

Figure 11 **Temperature of a stubble burn measured at the soil surface (°C) for chaff top and conventional windrows compared to spread stubble treatments**

Chitty and Walsh (2003) have studied the temperature obtained when the two different windrow treatments containing 15 t/ha of wheat stubble are burnt compared to a spread treatment containing 2.3 t/ha. Wheat stubble produced from headers consists of chaff and straw. The major difference between the two windrows is that the chaff top windrow is less compacted resulting in quicker burns at higher temperatures than the conventional windrow (Figure 11). These burn characteristics resulted in the chaff top windrow destroying 99 per cent of the ryegrass seeds compared to the conventional stubble windrow which only destroyed 82 per cent.

The actual burn time required to destroy weed seeds at set temperatures has been measured in kiln experiments (Chitty and Walsh 2003). Ryegrass seeds were destroyed within 60 seconds at 250 °C and within 20 seconds at 400 °C (Chitty and Walsh 2003). Wild radish pods are destroyed within 30 seconds at 400 °C and within 10 seconds at 500 °C (Walsh et al. 2005).

There are two problems with the use of the windrow system to destroy ryegrass seeds. First, windrows are difficult to burn once they have become wet. To reduce the risk of the windrow becoming wet requires early burning. Currently most burning of windrows occurs under a fire permits system that issues the permits immediately after the lifting of the summer fire restrictions.

Second, care is required to prevent the fire spreading. A number practices can minimise the risk of the fire spreading into adjacent stubble.

- Adjust comb height so that at least inter stubble rows contain 1.5 t stubble/ha, giving concentrated stubble windrow levels of 20–40 t/ha. This distribution of stubble will produce a fire hot enough to destroy weed seeds but leave enough stubble between the burnt windrows to protect the soil from wind erosion.

- Align windrows perpendicular to the prevailing winds. This has the effect of reducing the speed of travel of the fire while allowing the wind to fuel the fire from the side of the windrow. The net effect is a hot slow fire that burns to the soil surface where weed seeds are present. The optimal alignment for this burning pattern is facilitated by seeding and harvesting in an up and back pattern.
- Use up and back seeding and harvesting so that stubble can be held between two seeding rows (Photograph 2), so that the wheat stems act to hold the windrow in position over summer. This strategy also keeps the windrow from crossing over seeding rows, which appears to reduce the spread of the fire. It would be of interest if tramline farming with auto steer systems could reduce the occurrence of windrows crossing over previous seeding rows.

Photograph 2 **Placement of stubble windrow between two rows using a stubble chute attached to the rear of a header**

- Light grazing with sheep can remove some of the leafy materials attached to the stubble. It has been observed that the extra leaf material of barley stubbles make it unsuitable for containing the fire within the windrow.

5.3 Post harvest

5.3.1 Management options

Farmers will often minimise the management of stubbles at harvest due to the higher cost of running the header and reduced speed of harvest. Post harvest management to reduce stubble levels then becomes necessary. Options include slashing, windrowing, raking and burning or baling of windrows, ploughing of stubble and burning of stubble. Livestock can also be used to reduce stubble levels but at the cost of trampling the stubble resulting in increased stubble handling problems at seeding.

An estimation of cost for these various operations is presented in Table 5. Ploughing of stubble is a relatively expensive operation and is probably only done when control of summer weeds is required.

Table 5 **The cost of various post harvest stubble management options**

Operation	Cost ($/h)	Operation rate (ha/h)	Cost $/ha
Slasher	110	15.5 m width at 7.5 km/h = 11.6 ha/h	$9.5
Stubble raking	110	9.5 m width at 10 km/h = 9.5 ha/h	$8.5
Burning windrow	40	50 ha/h	$0.8
Ploughing	110	12.5 m width at 5 km/h = 6.1 ha/h	$18.0
Burning	40	100 ha/h	$0.4

5.3.2 Grazing

If you are managing stock on stubble you will need to calculate the number of days grazing which can be obtained from the stubble level (Equation 2).

Equation 2 $$Grazing\ days = \frac{Amount\ of\ stubble\ to\ be\ removed}{Rate\ of\ removal\,(kg/head/day)\ x\ stocking\ rate\,(DSE/ha)}$$

For example a 1.6 t/ha wheat yield with a harvest index of 0.35 will give 2.9 t stubble/ha. Using a tillage system that buries 50 per cent of stubble means only 1.4 t/ha is available for soil erosion prevention. Thus 0.4 t/ha can be safely removed by grazing. This can be achieved by grazing for 50 days at a stocking rate of 4.5 dry sheep equivalent/ha and a feed intake rate of 2 kg/head/ha. However, stock graze paddocks unevenly and this could lead to some areas being overgrazed. To avoid this, grazing will need to be closely monitored, especially on coarse textured soils.

5.4 Seeding

5.4.1 Tillage practices

Ploughing was the main tillage practice used up to the mid to late 1980s (White 1990). It involved turning over the upper layer of soil and bringing subsoil to the surface with the effect of burying both weeds and crop residues, allowing them to break down. Once ploughed the field was typically left to dry out, and then harrowed before seeding with a combine. Hence, seed bed preparation could take up to three separate operations. In the early 1990s herbicides replaced tillage as the main method of weed control, and the chisel plough was modified as reduced tillage practices for the placement of seed and fertiliser were developed. Under this system the seeding operation is conducted using a single pass operation.

Valzano et al. (2005) divided current tillage practices into three categories, from least to most soil disturbance.

- **No tillage** (NT), zero tillage (ZT) and direct drill (DD) systems are defined as narrow or knife-point seeding with aligned press wheels that results in less than 20 per cent topsoil disturbance (Derpsch et al. 2006). Harrows are not used. Weeds are controlled with herbicides and there may be limited or no grazing. Ground disturbance is kept to a minimum at sowing time and seedbeds are not tilled prior to sowing. Stubbles are usually retained on the soil surface and are partly covered by soil thrown up by the knife points from the seed row into the inter row. This soil throw also creates a furrow that can harvest water and increase crop germination.
- **Reduced tillage** (RT) or minimum tillage (MT) systems minimise soil disturbance, while at the same time creating a viable seedbed for crop growth. Landholders practising reduced tillage may use cultivation implements that minimise the area, depth and extent of soil disturbance, thus limiting the overall impact of cultivation on the physical properties of the soil. In WA this practice consists of using wide points with seeding done in a single pass. As with no-tillage systems, weeds and disease are usually controlled with herbicides and grazing. Stubbles are usually burnt and/or incorporated into the soil.
- **Conventional tillage** (CT) system one or more tillage operations will be carried out prior to sowing a crop. The extent of tillage will vary depending upon crop variety grown, soil type and climate. Tillage implements may differ from those used for reduced tillage practices, and result in more extensive soil disturbance. Conventional tillage is used to control weeds, pests and diseases. Also stubbles are usually burnt in this system.

Current minimum tillage practices are described as follows:

- **Direct drill** (DD)—wide tine points are used to give a greater than 20–30 per cent cultivation of the soil surface. Direct drill is also referred to as 'full cut'. The tines cultivate the soil and provide a disturbed seed bed.
- **No tillage** (NT)—narrow tines commonly referred to as a knife points are used, resulting in 5–20 per cent cultivation of the soil surface. The tine creates an opening for the placement of the seed and fertiliser and is followed by a press wheel to close the slot.
- **Zero tillage** (ZT)—flat discs are used to create an opening in the soil which is followed by a tine to deliver the seed and fertiliser into the slot and a press wheel to close the slot.

This minimal or no-tillage system with stubble retention is often referred to as conservation farming. The practice is suited to the coarse texture soils of Western Australia where climatic conditions can result in large wind and water erosion events. Currently, 88 per cent of northern and central wheat farmers use a no-tillage system for a proportion of their cropping programs (D'Emden and Llewellyn 2006; D'Emden et al. 2009). Nevertheless, it is still a fairly recent phenomenon, with only 15 per cent of WA adopters reporting minimal tillage use before 1994.

The amount of stubble incorporated varies greatly according to the following factors:

- Harvest height or straw length and how the stubble is distributed from the header (windrowed, spread, baled or removed in chaff cart).
- Incorporation by tillage systems will range from complete incorporation using a plough or offset discs, to partial incorporation using narrow points 5–10 mm (RT) or wide points 10–15 mm (CT), to minimal incorporation using knife point widths of 2–5 mm or discs (NT).
- Row spacing can range from 9 to 36 cm; the greater the row spacing the less stubble incorporation.
- The seeding bed can be enhanced using either press wheels or harrows.
- Seeding parallel to previous cultivation minimises incorporation whereas sowing at right angles encourages incorporation.

5.4.2 Seeding bar

The horsepower required to pull modern deep-blade no-till seeding bar ranges from 3.7 to 7 kW (5 to 9 hp) per tine at operating depths of 13 to 23 cm. Thus, a 12 m (40 ft) machine on 25 cm spacing (48 tines) requires approximately 284 kW (380 hp) using 18 cm (7") blades. These ratings obviously depend on soil types, moisture levels and tine spacing. As a general rule of thumb, a tine will require one horsepower per inch of blade used, thus a 5" blade uses 5 hp per tine and an 8" blade uses 8 hp per tine (www.ausplow.com.au/deep-blade-system/).

Riethmuller (1988) measured the draft requirements of tillage tools in Western Australia and found the pulling force or draft increased with working depth and ground speed for all tillage tools. Fuel consumption was also linearly related to draft, depending on the tractor type (4WD, front-wheel-assist or 2WD) and soil conditions (firm, tilled or soft). For example, in the past a typical primary tillage scarifier working at 75 mm deep on a sandy clay loam soil at 8 km/h pulled by a 4WD tractor on firm soil uses around 8 L/ha of diesel fuel. Interestingly, no-till deep-blade seeder uses about the same fuel per hectare as primary tillage. Although the wider tine spacing and narrower point width reduces fuel use, the extra working depth increases fuel use. Some no-till disc machines that do not work deep have much lower draft

and therefore much lower fuel use. However, disc machines capable of deep working are generally also heavy to allow soil penetration in hard soils and are thus heavy to pull uphill, resulting in about the same fuel use as tine machines (Riethmuller 2009 pers. comm.).

Seeding bar design and set up can be used to address clumping and blockages at seeding (Collins 2006) with stubble levels greater than 3 t/ha. Seeding into these stubble levels is likely to be difficult, especially if the stubble is long, wet and laying flat on the soil surface.

5.4.3 Design

Modern seeding bars designed to handle stubble generally have:

- a minimum ground clearance of 50 cm
- five ranks 65–80 cm apart
- tines placed across the seeding bar to give one row spacing and two ranks apart or two row spaces and one rank apart
- tines with a curved shape on the leading edge with a diameter of 40–85 mm
- long draw bars to reduce turning radius
- wheel placement outside the frame to provide greater flexibility with tine placement
- long seeders that can reduce seeding depth control (though this problem can be overcome by using pressure wheels with individual pressure controls)
- knife points, which are generally less likely to catch residue than wide points
- shallow working and lower speed to give less clumping due to the reduction in soil throw.

5.4.4 Set-up

There are stubble management tools that can be fitted to seeders to assist in handling stubble:

- Stubble tubes, when fitted well, are cheap and simple way of stopping stubble from wrapping around tines. They are designed to protect the angle where the tine and point meet, and are placed low enough to be within the soil flow when the tine is in the working position. It is important that the tube is secured well and there is no movement. Steel is the best tube material.
- Row cleaner wheels are a more expensive option than stubble tubes and are more suited to wider row spacings.
- Disc coulters cut the stubble better then row cleaners and result in greater soil throw for incorporation of herbicides.
- Treadwheels (stubble star) are an experimental concept that pin the stubble where it lies rather than moving it out of the way.

5.4.5 Control traffic system

In control traffic systems, machinery travels down designated tramlines (Photograph 3). The main benefits of control traffic system are associated with restricting the areas of compaction to tramlines and by reducing areas of overlap (Webb et al. 2004).

Photograph 3 **Tom Lewis from Bruce Rock WA seeding using tramlines and auto steer with dGPS in 2005**

A tramline farming system enables inter-row or on-row sowing. The option of tramline farming has the potential of widespread additional benefits. When wheat stubble is retained, inter-row sowing results in reduced clumping and improved crop establishment (see Photograph 4).

Photograph 4 **Clumping versus no clumping as a result of inter-row sowing** Photograph: M McCallum

Electronic systems are based on differential global positioning systems (DGPS) satellite range with a level of precision from 100 cm to 2 cm (Webb et al. 2004). Systems range from l-band or high precision dual frequency that uses a series of up to 12 satellites with differential correction provided by a network of precise surveyed reference points via a geostationary satellite, to a real time kinematic (RTK) system with differential correction from a local on-farm base station to obtain precision to 2 cm.

Inter-row sowing is best achieved with a ±2 cm RTK system with an on-farm base station. This is because repeatable precision enables the sowing rig to come within ±2 cm of the sowing rows from the previous year and be able to hold a straight line down the length of the field.

Sub-metre auto steer (±10–20 cm) does not have this level of precision, but the A:B line can be reset by eye and inter-row sowing can be attempted the following year. This will not be as successful as a ±2 cm system, and allowances will have to be made for some overlap to compensate for the lower level of precision.

Some rules to follow for inter-row sowing:

- You must keep the same row spacing year after year.
- The base station must remain at the same location for a particular paddock for subsequent years.
- Your auto steer must have the ability to store and recall an A:B line for a particular paddock.
- Your auto steer must have a 'nudge' feature in order to move the required distance to go inter-row.
- It is best to sow in the same direction each year for each run, since sowing rigs will crab, but hopefully crab in the same pattern as the previous year.

5.4.6 Crop variety

The semi-dwarf trait is used to increase harvest index and increase straw strength (Blakely Paynter personal comm.). Tall varieties have a greater risk of lodging and greater unevenness in head height. They also have a larger amount of stubble that might need to go through the header, slowing down harvest and resulting in more wear on the header. However, not all semi-dwarf trait varieties are short as there are tall semi-dwarf varieties like Gairdner and short semi-dwarf varieties like Baudin. In experiments, Gairdner and Baudin were observed to have the same maturity and produced 4.0–4.3 t grain/ha but Baudin produced similar amount of straw even though it had a lower plant height (Table 6).

Table 6 **Plant height, biomass (t/ha), grain (t/ha) and stubble yield (t/ha) for various varieties with different plant heights (cm)**

Variety	Plant height (cm)	Total biomass (t/ha)	Grain yield (t/ha)	Straw yield (t/ha)	Harvest index
Gairdner	68	10.9	4.0	6.9	0.37
Baudin	59	11.4	4.2	7.2	0.37
Vlamingh	72	11.0	4.1	6.8	0.38
Dash	65	10.2	4.3	5.9	0.42
LSD (0.05)	3	1.4	0.1		ns

5.4.7 Water conservation

Crop residues used for mulching are well known to reduce soil evaporation, decrease diurnal soil temperature variations and increase saturated soil hydraulic conductivity (Bristow and Campell, 1986; Bussiere and Cellier, 1994) leading to reduced soil water loss (Dahiya et al. 2007).

Stubble retention and reduced tillage offer increased productivity of wheat through greater water conservation (O'Leary and Connor 1997a, 1997b; Cantero-Martinez et al. 1995). This benefit varies from year to year due to the interaction with soil nitrogen supply. For example Cantero-Martinez et al. (1999) examined the effect of different conventional and conservation farming systems on soil water and response to applied nitrogen fertiliser (Table 7). It was observed that conservation system soil profiles contained 83 mm more water but less nitrogen than the conventional system. When nitrogen fertiliser was applied there was a reduction in wheat grain yield. The adverse effect was greater in the conventional system compared to the conservation system, due to the higher nitrogen levels and lower water levels under the conventional system.

Table 7 **The effect of conventional and conservation farming systems on soil water and soil nitrogen content, and wheat grain yield (t/ha)**

Nitrogen treatment	Available soil water (mm)	Inorganic soil n (kg N/ha)	Biomass anthesis (t/ha)	Maturity (t/ha)	Grain yield (t/ha)	Grain size (mg)	Harvest index (mg)
			Conventional farming system				
-N	251	239	7.1	9.3	3.4	32	0.36
+N	234	230	7.2	8.1	2.7	30	0.34
			Conservation farming system				
-N	341	145	7.2	10.0	3.8	35	0.38
+N	316	205	7.9	10.5	3.7	32	0.34
LSD	56	85	2.2	2.2	1.0	2	0.04

5.4.8 Row spacing

When sowing lupins into wheat stubble, increased row spacing has the effect of reducing clumping and blockage problems at seeding. French (2005a) conducted an experiment to measure the effect of row spacing on lupin yield (Table 8). Lupin yield response to row spacing was driven by radiation interception and water use patterns. It was observed that lupins grown in wide rows intercept less solar radiation than when grown in narrow rows, and therefore initially grow more slowly. They also extract soil water more slowly, which means they can continue growing for longer. The observed yield response depends on the interaction of these two effects. The narrowest spacing usually produced the most dry matter at maturity, but in wide spacings this dry matter was more efficiently partitioned into grain as a result of more favourable water relations during grain filling. At the Mullewa site yields actually increased, and when planted in rows 100 cm apart. However, planting in 100 cm rows reduced yield at Wongan Hills.

Table 8 **The effect of row spacing on lupin grain yield (t/ha) grown at three sites in 2004**

Stubble	Spacing	Mullewa	Wongan Hills	Merredin
Retained	25 cm	1.0	1.6	0.6
	50 cm	1.5	1.6	0.6
	75 cm	1.3	1.6	0.6
	100 cm	1.6	1.4	0.7
LSD (P = 0.05)		0.3	0.2	0.2

6. Soil carbon

6.1 Introduction

Janzen (2004) observed how research on the cropping system carbon cycle has changed over the past decades. Initially research was directed at examining how to prevent a collapse in productivity due to the observation that a rapid decline in soil carbon followed cultivation (Grace et al. 1995). This was followed by research on developing reduced tillage cropping systems that maintained soil carbon content (Chan and Heenan 2005). Recently the problem of greenhouse gas emission (carbon dioxide and nitrous oxide) from the agricultural section has renewed interest in the study of tillage systems and stubble retention practices (Baker and Griffis 2005; Verma et al. 2005; Adviento-Borbe et al. 2007; Chatskikh and Olesen 2007).

The aim of this section is to examine the impact of tillage and stubble retention on soil carbon. It highlights how the direction of research has change from developing cropping practices which reduce the impact on soil carbon to examining the impact of cropping practices on greenhouse emissions.

Stewart (2006) argues that maintenance of soil carbon levels is critical for the sustainability of dryland agriculture systems. He states:

- in many cases, cropping of these lands could not be sustained because of insufficient and highly variable precipitation that resulted in a rapid decline of soil carbon
- in some cases, when cropping was terminated and these lands were returned to grazing lands, they were less productive than prior to cultivation.

Many chemical compounds or gases found in the earth's atmosphere act as greenhouse gases. When sunlight strikes the earth's surface, some of it is reflected back towards space as infrared radiation (heat). Greenhouse gases absorb this infrared radiation and trap the heat in the atmosphere. The main greenhouse gases associated with cropping systems are carbon dioxide and nitrous oxide. Robertson and Grace (2004) developed the term global warming potential (GWP) to provide a means for comparing the relative effects of one source or sink of greenhouse gas to another for any particular agricultural system. Global warming potential is measured in CO2-equivalents (IPCC, 1996). Nitrous oxide has a far lower atmospheric concentration than carbon dioxide but its global warming potential is significantly higher. This is because nitrous oxide is long-lived within the atmosphere: the 100-year nitrous oxide global warming potential (296 CO2-equivalents) is not much different from its 20-year global warming potential (275 CO2-equivalents) (IPCC 2001).

The Task Group on Emissions Trading (2007) recommended that the agricultural sector not be covered under the National Emission Trading Scheme (2006) because of the lack of reliable measurement methodologies at the farm level and the complexity and cost of verifying greenhouse gas emissions and carbon sequestration. It has been suggested that research effort should be directed at developing a greater understanding of practical abatement opportunities for the agricultural sector, and improving measurement of agricultural emissions and carbon sequestration.

6.2 Function

Baldock and Skjemstad (2001) provide a summary of the function of soil carbon within the soil. Soil carbon impacts on the soil's biological, physical and chemical processes with strong interactions between the three functions (Figure 12).

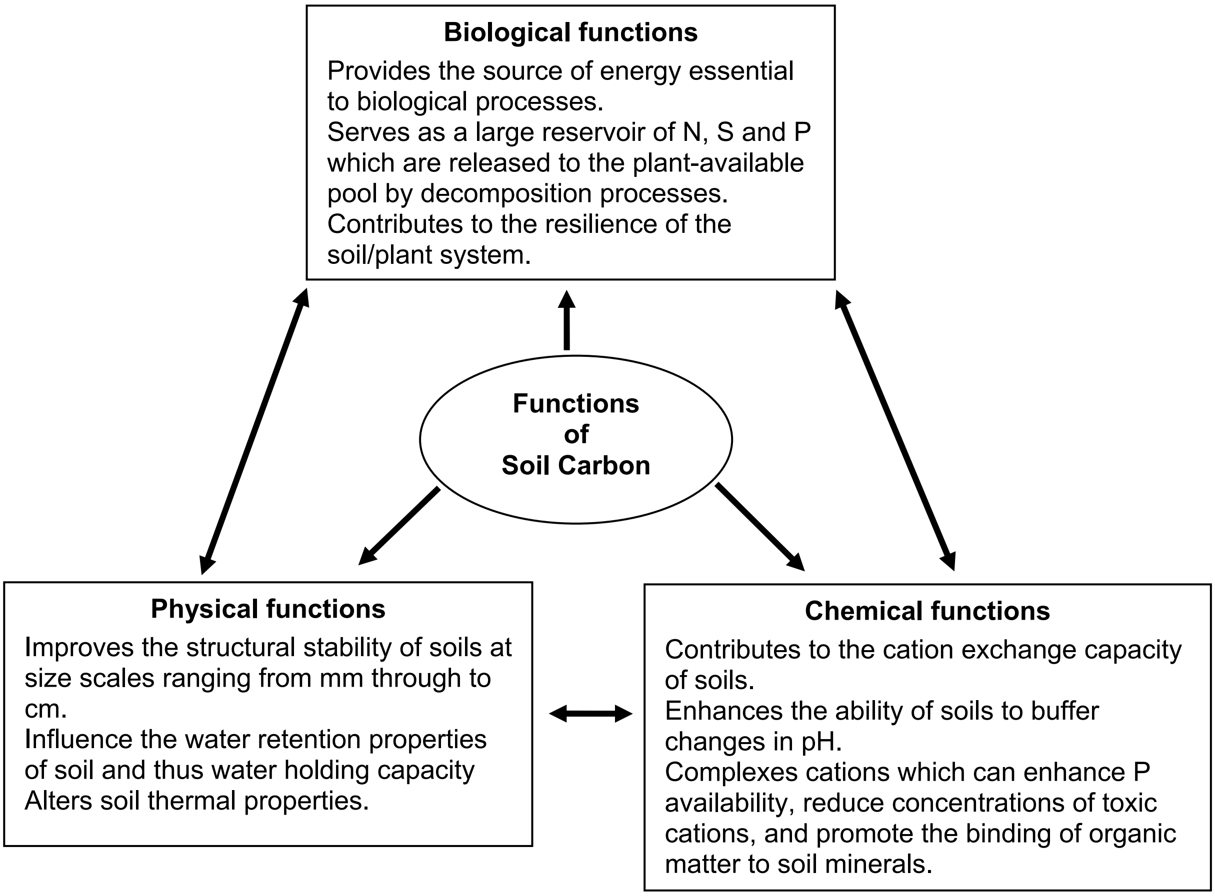

Figure 12 **Functions ascribed to soil carbon (Baldock and Skjemstad 2001)**

Soil carbon content will vary considerably within specific soil types due to variation in management practice, climate, soil mineral composition, soil biology (vegetation and organisms), topography and the frequency of various catastrophic natural or human-induced events (fire, water erosion and wind erosion). These factors are referred to as soil forming factors.

The soil carbon content of soils is determined by the net carbon balance or carbon inputs minus carbon losses. In agricultural lands soil carbon values will tend towards equilibrium values dictated by the soil forming factors. However, continual changes in management and cropping practices will create a system in which soil carbon levels are always in a state of flux, increasing with some factors and decreasing with others. If management practices are left in place for long enough, it is possible for agricultural soils to attain equilibrium in soil carbon values indicative of rotation and management.

6.3 Conceptual model

Six et al. (2000) hypothesise that macro-aggregate turnover and soil carbon dynamics are closely linked. Jastrow (1996) observed that most of the accumulated soil carbon occurred in the mineral-associated fraction of macro-aggregates. This suggests inputs of organic debris

were rendered relatively rapidly into particles or colloids that are associated with mineral matter. Thus the soil carbon is physically protected, slowing decomposition and promoting the development of stable micro-aggregates within macro-aggregates. It is argued that linking these processes gives a mechanistic explanation as to why there is a greater accumulation of soil carbon in the surface soil layers under no-tillage agriculture. That is, a reduction in tillage allows aggregation processes to re-establish, thereby rebuilding the physical protection of the soil carbon. In contrast, ploughing of the soil and burning of crop residues result in a decline in the soil carbon levels (Grace et al. 1995; Reicosky, 2003) and a decline in soil structure (Whitbread et al. 1998).

Soil aggregates play a major role in the physical protection of soil carbon by controlling microbial access to substrates. Relatively labile carbon can be physically protected from decomposition if it is incorporated into soil aggregates or deposited in micropores that are inaccessible even to bacteria (Figure 13). In general, macro-aggregates or aggregates with a diameter greater than 0.25 mm are sensitive to soil disturbance. In contrast, micro-aggregates or aggregates with diameter less than 0.25 mm, are more stable and have a higher resistance to soil disturbance (Tisdall and Oades 1982).

In general, conventionally tilled soil tends to be dominated by bacteria because the mixing of the litter with the soil allows direct contact between the bacteria and the substrate (Beare et al. 1992). In contrast, fungi tend to dominate in no-tillage systems because hyphae are required for the micro-organism to contact litters left on the soil surface (Beare et al. 1992; Guggenberger et al. 1999). In the presence of fungal-dominated pathways, soil carbon cycling tends to lead to a build-up of soil carbon in the form of relatively stable polymers of melarnin and chitin (Stahl et al. 1999; Bailey et al. 2002).

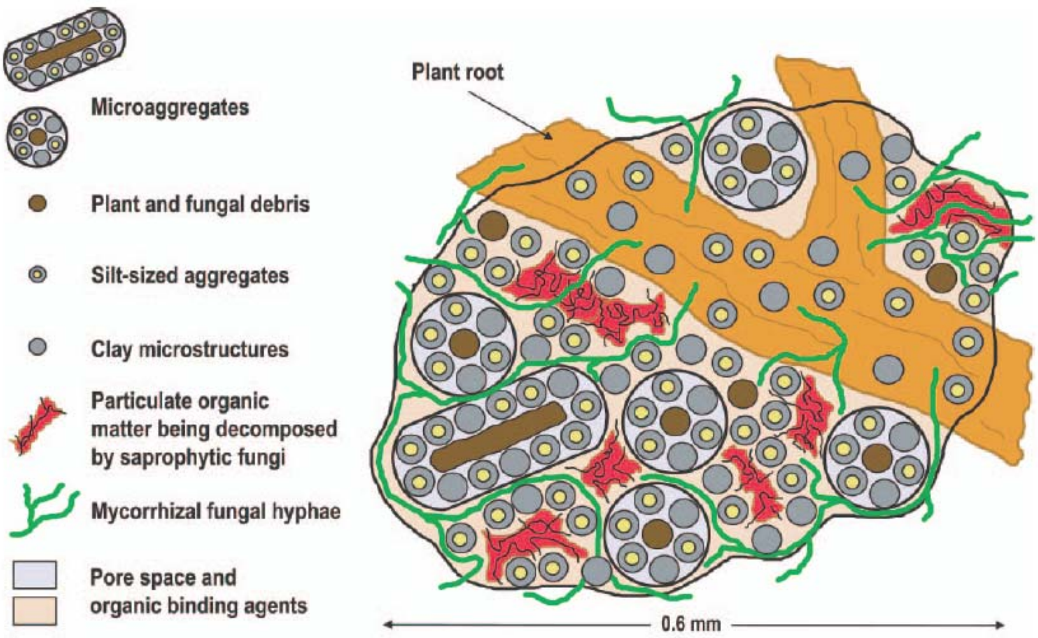

Figure 13 **Conceptual diagram depicting the hierarchical organisation of micro-aggregates within a macro-aggregate (Jastrow and Miller 1998)**

The processes of soil aggregate stabilisation are complex and involve a variety of binding mechanisms interacting at a range of spatial scales (Tisdale and Oades 1982). They suggest that plant roots and fungal hyphae bind micro-aggregates into macro-aggregates. Jastrow et al. (1998) concluded that roots and mycorrhizal hyphae are the key binding agents for

macro-aggregate stabilisation in a system recovering from disturbance. It appears that very fine roots have an indirect impact on soil aggregate formation through their strong associations with mycorrhizal fungi and their influences on microbial activity.

6.4 Soil carbon pools

In general, soil carbon can be divided into a number of pools or fractions based on decay rate. The most active organic pool is often the most important for soil fertility, both chemical and physical. Defining the nature and quantity of this active pool has become important because this pool is a more sensitive indicator of short-term and medium-term changes in soil carbon in response to different management practices (Whitbread et al. 1998; Chan 1997).

The relative size of these pools can be derived by running the carbon models until an equilibrium pool structure is obtained for the particular climatic conditions and management practices. Alternatively, laboratory techniques can be used to estimate the size of these pools. There are two laboratory techniques used to fractionate soil carbon: physical and chemical extraction.

- Camderdella and Elliot (1992) provide an example of a physical fractionation technique. In this method soil carbon is physically separated into two pools. The first pool, or the more active soil carbon pool, is referred to as particulate soil carbon and consists of soil carbon with a particle size greater than 53 μm. The less active soil carbon pool, or soil carbon with particles size of less than 53 μm, is further divided into charcoal and non-charcoal pools.
- Blair et al. (1995) provide an example of a chemical extraction technique in which 333 M $KMnO_4$ is used to oxidise a fraction of the soil carbon. The extracted soil carbon fraction is considered to be the more active soil carbon pool and is referred to as labile soil carbon.

In general, chemical extraction techniques are more popular with commercial soil testing laboratories than physical extraction techniques because they can be adopted at lower cost. However, Skjemstad et al. (2006) have recently shown particulate soil carbon to be a more sensitive measure of the rapid gains in soil carbon than labile soil carbon when pastures are established on degraded soils.

6.5 Status

The current soil carbon content of the region is strongly related to rainfall or biomass production (see Figure 14). Soil carbon status can be separated into six broad groups: < .5 per cent, 0.5–0.75 per cent, 0.75–1.5 per cent, 1.5–2.0 per cent, 2.0–4.0 per cent and > 4.0 per cent (National Land and Water Resources Audit 2001). These groups are correlated with the positive impact of rainfall and the negative impact of temperature on the net carbon balance. As the climate becomes more arid, soil carbon values become progressively lower due to lower levels of production. The broad temperature effect can be seen in WA, moving from the cooler southern coastal region (1.5–4.0 per cent), through the central wheatbelt (0.75–1.5 per cent), to the warmer, northern wheatbelt and the Geraldton sandplain (< 0.75 per cent). Grazing lands had higher soil carbon levels than those measured in the cropping zone, as illustrated by the northern wheatbelt where low soil carbon values are associated with high cropping intensities on sandy soils.

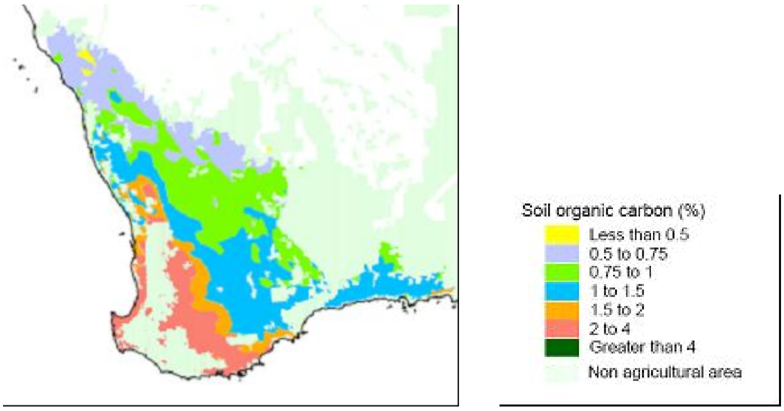

Figure 14 **Soil carbon status (per cent) of the agricultural region of WA (National Land and Water Resources Audit 2001)**

An analysis of the quality of the soil carbon is provided in Table 9. The data illustrates how soils of the southern fringe of the wheatbelt (Williams and Narrogin sites) have a greater proportion of soil carbon (0.14–0.36) in the labile soil carbon fraction compared to the sites of the northern wheatbelt (0.03–0.05). Soil carbon contains nitrogen (N), sulphur (S) and phosphorus (P). The C:N ratio was observed to range from 7 at the Mullewa site to 19 at the Williams site. The average C:N ratio was calculated to be 10, which is lower than the generally accepted ratio of 13, perhaps because most of the sites (8 of the 11) were associated with long-term cropping. The C:P ratio was observed to range from 33 to 76 and the C:S ratio from 62 to 124.

Table 9 **Soil carbon (%), labile soil carbon (%), total N (%), P (%) and S (%) contents for eleven sites located within the wheatbelt of WA (Anderson and Fillery unpublished data)**

Site	Clay (%)	Gravel (%)	Soil carbon (%)	Labile soil carbon (%)	Total N (%)	Total P (%)	Total S (%)	C:N	C:P	C:S
Williams	1.0	40	5.68	2.04	0.30	0.075	0.069	19	76	82
Arthur River	0.5	60	1.51	0.41	0.18	0.021	0.012	9	71	124
Narrogin	2.0	46	1.83	0.80	0.28	0.043	0.027	7	43	67
Beverley	3.0	0	1.16	0.36	na	0.021	0.013		55	89
Moora	4.0	32	1.68	0.43	0.19	0.030	0.020	9	55	86
Mullewa	0.5	0	0.36	0.16	0.05	0.007	0.005	7	53	67
Carnamah	7.0	38	0.65	0.18	0.06	0.019	0.008	10	34	81
Latham	3.0	0	0.70	0.28	0.05	0.014	0.008	13	52	87
Wubin	2.0	0	0.62	0.15	0.06	0.015	0.010	10	40	63
Kalannie	6.0	0	0.58	0.20	0.07	0.018	0.009	9	33	62
Ballibu	2.0	0	0.68	0.23	0.06	0.013	0.007	12	53	97

6.6 Soil structure

Since tillage and stubble management practices can impact on soil carbon and labile soil carbon contents, which in turn impact on soil structure, it is important to examine soil structure to gain an overall understanding of the effects of these practices.

Soil structure is the architecture of the soil as defined by the arrangement of soil particles (Quirk and Murray 1991). It is a complex physico-chemical interaction of the colloidal surfaces of clay and soil carbon that enables soil to form aggregates (Hamblin 1987). The

pores that form are very important in determining the flow and storage of water and nutrients. In this context the important aspect of soil structure is the interaction between clay particles and water for soils with clay contents greater than 8–10 per cent. For soils with lower clay content the clay particle interaction with water still gives rise to swelling but this is internally accommodated within a matrix of coarse particles.

Soil structure is described in terms of it porosity, strength (ease of penetration), stability and resilience (ability to reform aggregates). A well structured soil will have a large proportion of aggregates in the range 0.5–2.0 mm that are not easily broken down. It will have high porosity to water; be easily cultivated and penetrated by plant roots, stable when wet, and when mechanically disturbed aggregates can reform. Soil with poor structure will have lower infiltration rates, seedling emergence, aeration, trafficability and workability than well-structured soils.

There are two processes related to soil structure stability: slaking and dispersion:

- **Slaking** is a chemical process that describes the disaggregation of soil aggregates when exposed to water. It is related to aggregate stability or the ability of the aggregate to resist breakdown into smaller units when placed in water or exposed to intensive rainfall. Small quantities of soil carbon and oxides can moderate the effects of rapid wetting to such an extent that such aggregates maintain their stability even when the soil is wet rapidly.
- **Dispersion** is a physical process that describes the way in which individual clay crystals migrate away from each other as a result of a net excess of repulsive over-attractive electrical forces (Hamblin 1987). Clay particles are negatively charged and this is compensated by hydrated cations that maintain electrical neutrality. Soil structure stability increases when there is a high proportion of exchangeable divalent cation (Ca^{2+}) present. Soil structure stability can decrease when these divalent cations are replaced by single valent cations (Na^{+}).

Soil carbon stabilises aggregates by acting as bridges to strengthen the structure of coarse pores. This becomes important as the intensity of a rainfall event increases. The disintegration of aggregates > 250 mm due to agricultural practices can lead to blockages of pores that reduce infiltration and increase the risk of water erosion (Tisdall and Oades 1982).

6.7 Management impacts

6.7.1 Soil carbon status

Experimental studies

Traditional farming practices such as burning, removing stubbles and conventional tillage result in a decline in soil carbon (Dalal and Mayer 1986; Chartres et al. 1992). In contrast, reduced or no tillage, residue retention, the use of green manure crops, pasture leys and application of organic materials result in an increase in soil carbon. The rate of change in the soil carbon content can be observed in long-term experiments. In South Australia, a 68 year wheat–fallow rotation resulted in soil carbon content declining from 2.7 per cent to 1.0 per cent (Grace et al. 1995). Under this system wheat grain yields could not be sustained (0.9 t/ha). In contrast, over the same time period, a wheat–oats–pasture–fallow rotation maintained a higher soil carbon content of 1.5 per cent and higher wheat grain yields (1.6 t/ha) than the wheat–fallow rotation.

Table 10 **Studies with significant tillage and stubble management effects on soil carbon summarised by Valzano et al. (2005)**

Author	Main findings
Blair et al. (1998)	Sugar cane trash burning resulted in greater soil carbon loss than equivalent trash retention plots.
Blair and Crocker (2000)	No-tillage plots had higher soil carbon levels than cultivated plots.
Carter and Mele (1992)	Soil carbon increase was found in direct drill plots compared with stubble burnt cultivated plots.
Cavanagh et al. (1991)	Higher soil carbon levels were found in direct drill plots compared with conventional tillage plots.
Chan and Mead (1988)	Higher soil carbon levels were found in direct drill plots compared with conventional tillage plots.
Chan and Hulugalle (1999)	Higher soil carbon levels in intensively were found in cropped plots compared with minimum tillage plots.
Chan et al. (1992)	No significant difference was found between conventional tillage and reduced tillage treatments, but a significant difference was found between direct drill stubble retained and conventional tillage stubble burnt.
Chan et al. (2002)	Soil carbon levels were significantly lower in conventional tillage plots compared with direct drill plots.
Conteh et al. (1998)	Higher soil carbon levels were found in cotton stubble incorporation plots compared with stubble burning.
Dalal and Mayer (1986)	Reductions in soil carbon and nitrogen were found in with increasing cultivation period.
Hamblin (1980)	Direct drill plots had slightly higher soil carbon levels than conventional tillage plots.
Hamblin (1984)	Soil carbon in conventional tillage plots was slightly lower than in equivalent direct drill and zero tillage plots.
Heenan et al. (1995)	Soil carbon and nitrogen were lost at slower rates in direct drill stubble retained plots than in conventional tillage stubble burnt plots.
Holford et al. (1998)	Soil carbon was lower in long fallow treatments compared with other rotation treatments.
Hulugalle and Entwistle (1997)	Soil carbon was significantly lower in conventional tillage plots compared with reduced tillage plots.
Hulugalle et al. (2002)	Decrease in soil carbon levels were found with increasing tillage time.
Loch and Coughlan (1984)	Soil carbon levels were higher in stubble retained compared with stubble burnt plots.
Macks et al. (1996)	Lower soil carbon levels were found in conventional tillage plots compared with direct drill plots.
Mason (1992)	Fallowing resulted in lower soil carbon levels than plots that were not fallowed. Lower soil carbon levels were found in stubble burnt plots than in stubble incorporated plots.
Smettern et al. (1992)	Higher soil carbon levels were found in direct drill plots than in equivalent conventional tillage treatments.
Sparrow et al. (1999)	Intensively cropped plots had lower soil carbon levels compared with intermittent cropping plots.
Standley et al. (1990)	Losses in soil carbon were less in zero tillage plots than in plots prepared with disc or blade ploughs.
Valzano et al. (2001)	Higher soil carbon levels were found in reduced tillage plots compared with direct drill plots.
White (1990)	Higher soil carbon and N levels were found in direct drill plots compared with reduced tillage plots.
Willis et al. (1997)	Significant differences were found between different tillage types.

Valzano et al. (2005) summarised the results of 56 studies with more than 20 significant tillage effects on soil carbon levels (see Table 10). In most instances increased levels of tillage or increased tillage periods resulted in reductions in soil carbon. There are confounding factors, however, that moderate the extent to which low or no tillage and stubble retention improves soil carbon levels. For example no-tillage can correct a soil problem which can result in greater biomass production and carbon input.

There are a number of possible mechanisms involved in tillage-induced reductions in soil carbon.

- The physical disruption of soil carbon may result in a higher rate of microbial breakdown. Syers and Craswell (1995) suggested that such a decline was due to increases in the decomposition rate by the shattering of macro-aggregates, mixing of surface soil and increases in the intensity and number of wetting and drying cycles. Oades (1993) stated that the repeated cultivation of soils combined with limited carbon inputs eventually results in major aggregate breakdown leaving the soil vulnerable to erosion and compaction.
- With the movement and incorporation of soil carbon deeper into a profile, moisture conditions facilitate microbial breakdown.
- The deterioration of the physical and associated structural properties of soil contributes to possible soil erosion and/or lower crop yields and dry matter production.
- Carbon sources can be physically removed by burning, grazing or baling.

Chan and Heenan (2005) published a study comparing the individual effects of stubble management and tillage and the interaction between these management practices on soil properties (Table 11). The no-till treatment had a higher soil carbon content (2.2 per cent) compared to the conventional tillage treatment (1.6 per cent) after 19 years. It was argued that the large loss in soil carbon associated with three tillage passes was due to disruption of the previous crop's root systems and incorporation of the stubble into the soil. This would have exposed the stubble and older soil carbon to conditions of accelerated decomposition. Retention of crop stubble resulted in higher soil carbon (2.0 per cent) compared to when stubble was burnt (1.8 per cent). Hence, it was concluded tillage had a greater impact on soil carbon than the burning of stubble. The interaction between tillage and stubble treatments was not significant. The decrease in soil carbon content due to stubble burning followed the same trend for both tillage treatments. For the short-term study at Temora, tillage treatments had smaller effects on soil carbon of only 0.3 per cent.

Roots are an important sink for the plant's photosynthate, with 30–50 per cent translocated to below-ground (Buyanovsky and Wagner 1997). Once in the root system this photosynthate is used for the structural growth of the root system; in autotrophic respiration; or is lost to the surrounding soil in organic forms. The relative importance of the contribution of root carbon to soil carbon was illustrated by Wilts et al. (2004) who estimated that the ratio of soil carbon content derived from below-ground plant carbon to that derived from above-ground was nearly 2:1. Chemical recalcitrance appears to slow root decomposition, and such recalcitrance may partially explain why roots have been found to contribute more carbon to the soil carbon pool than surface residues (Johnson et al. 2007).

Table 11 **Soil quality parameters of the 0–5 cm soil layer under different stubble management practices in the Wagga Wagga and Temora field trials (Chan and Heenan 2005)**

Treatments		Soil carbon (%)	Labile carbon (%)	pH	Water stable aggregates > 250 μm (% A_{250})	CEC (cmol/kg)
Tillage	Stubble					
Wagga Wagga (over 19 years)						
NT	SR	2.3	0.61	4.8	46.6	6.6
	SB	2.1	0.50	5.0	35.7	6.5
CC	SR	1.7	0.36	4.7	38.2	5.2
	SB	1.5	0.33	4.9	33.1	5.1
LSD		0.1	0.02	ns	2.2	0.5
Temora (over 5 years)						
NT	SR	1.8	0.38	5.0	57.4	6.4
	SB	1.9	0.36	5.1	56.9	6.6
CC	SR	1.5	0.29	4.8	46.3	5.1
	SB	1.6	0.29	4.8	45.1	5.5
LSD		0.1	0.02	0.1	3.6	0.8

SR stubble retained; SB stubble burnt; NT no tillage; CC conventional tillage; LSD least significant difference; ns not significant.

Labile soil carbon showed similar trends to soil carbon. However, conventional tillage resulted in a greater decline in labile soil carbon (38 per cent) compared to a 28 per cent decline in soil carbon. Long-term use of the no-till system resulted in greater macro-aggregate stability compared to conventional tillage. The impact of stubble retention on macro-aggregate stability was greater under the no-till system compared to the conventional tillage system (Table 11). In contrast, at the short-term site the no-till system resulted in greater macro-aggregate stability than conventionally tilled soil but stubble retention had no affect on macro-aggregate stability.

Highest average wheat yield was observed for the no-till stubble burnt treatment (3.8 t/ha). Retaining stubble and tillage resulted in a 0.15 t/ha decrease in wheat yield at the Wagga Wagga site. In contrast, there were no yield effects at the Temora site. Kirkegaard (1995) has reviewed long-term agronomic trials in Australia and reported a 0.02–0.31 t/ha reduction in wheat yield when stubble was retained rather than burnt.

A study in the wheatbelt of WA illustrated that reduced tillage had a variable impact on soil carbon levels (White 1990). Experiments compared zero tillage, direct drill and tilled using a combination of disc ploughing or scarifier. Crop stubbles or residues were removed by grazing and burning prior to seeding. At the friable red-brown loamy earth (xeralfic alfisol) site at Merredin, zero-tillage treatments had higher soil carbon content compared to disc plough treatments to a soil depth of 25 cm. However, the difference between these treatments only extended 10 cm down on a yellow earthy sand (typic xeric psamment) site at Wongan Hills and was confined to the top 5 cm on a non calcic brown earth (lithic alfisol) site at Avondale. Across the three sites zero tillage resulted in an 8–20 per cent increase in soil carbon in the 0–5 cm soil layer compared to tilled soil.

Roper (2005) studied the impact of tillage treatments on microbial functions including organic matter turnover. The tillage treatments ranged from cultivation with rotary hoe, conventional cultivation (a single pass with 130 mm wide tines to a depth of ~75 mm), no-tillage (triple disc drill) and no disturbance (pasture). The experiment went for seven years (1998–2004). The

rotary hoe resulted in a steady decline in several parameters and by year seven, total nitrogen and carbon had declined by ~25 per cent compared with other treatments, while microbial biomass, microbial activity and cellulase activity declined by 30–50 per cent. The effect of tillage practice on grain yield was far less defined than on other measures, but some notable patterns developed. In the first years of the trial, lupin yields were unaffected by tillage, but in year 6 (2003), lupin yield in rotary hoe was less (1.6 t/ha) than in conventional cultivation (1.9 t/ha) or no tillage (2.0 t/ha). In the first 2 years of wheat (1999, 2001) cultivation favoured wheat yields presumably because cereal root pathogens were disrupted, but later in the trial (2002) wheat yield in rotary hoe was less (1.4 t/ha) than conventional cultivation (1.6) and no tillage (1.5), possibly due to greater moisture constraints under rotary hoe. In 2004, grain yield was greater for the no-tillage treatment even though there were patches of rhizoctonia root disease in the no-tillage and conventional cultivation treatments but not under rotary hoe.

Riethmuller (2005) studied the long-term benefits of stubble retention compared to stubble removal by burning. This site, established in 1987, is located on a friable red-brown loamy earth (Schoknecht 2002) at the Merredin Research Station. Management practices changed over the course of the experiment to reflect changes in farming practices within the Merredin region to include the introduction of wheat/pulse rotation in 1994 and the adoption of reduced tillage in 1995. The reduced tillage practices included the use of 50 mm knife points and phoenix harrows with all non-sowing points removed. In 2004, Janke 80 mm wide press wheels replaced the phoenix harrows (Riethmuller personal communication).

Grain yield production (t/ha) is presented in Figure 15. Wheat was grown in all years except 1994 when faba beans were grown, 1996 chick peas, 1999 canola, 2000 a drought occurred and the site was chemically fallowed, 2002 lentils (dry seasonal condition resulted in poor yields) and 2005 field peas. There was an initial negative effect (–5.7 to –2.4 per cent) of retaining stubble in the first 6 years of the experiment. This was followed by a positive response (4.2 to 17.5 per cent) for wheat crops grown after 1992.

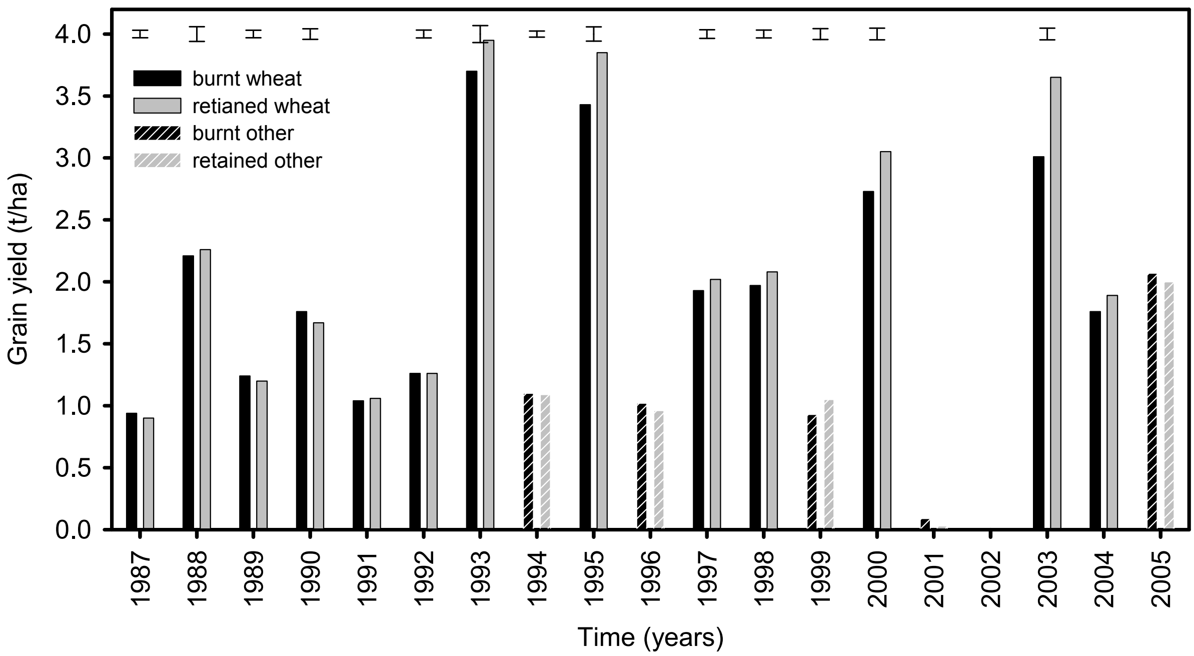

Figure 15 **Crops grain yield (t/ha) grown on burnt and retained treatments 1987–2005**

Soil carbon content was higher for the retained stubble treatment (1.10 per cent) than for the stubble burnt treatment (1.00 per cent) for the soil layer 0–5 cm measured in September 1995. Higher soil carbon content was found for the retained stubble treatment (1.04 per cent) than for the burnt treatment (0.99 per cent) measured in October 1997. By 2003 soil carbon content was 1.2 per cent for the retained stubble treatment and 1.0 per cent for the burnt treatment (Hoyle et al. 2006).

Changes in soil carbon are more accurately assessed expressing the results in units of t C/ha instead of as a percentage because the former calculation takes into account the differences in the bulk density of the two stubble treatments. Hoyle et al. (2006) calculated soil carbon in the 0–5 cm to be 8.7 t C/ha for the stubble retained treatment compared to 6.0 t C/ha for the burnt treatments. Microbial biomass carbon content was 153 kg C/ha or 1.76 per cent of soil carbon for the stubble retained treatment compared to 98 kg C/ha or 1.63 per cent of soil carbon for the stubble burnt treatments. Microbial biomass N was 24 kg N/ha or a microbial C/N ratio of 6.6 for the stubble retained treatment compared to 25 kg N/ha or a microbial C/N ratio of 3.9 for the stubble burnt treatments.

Modelling studies

The soil carbon cycle under various climatic conditions and management practices for different soil types is a complex process. Thus to extend the results obtained from long-term experiments, soil scientists have developed various simulation models. The first soil carbon model, ROTHC, was developed from results obtained from the Rothamsted long-term experiment (Jenkinson 1990; Jenkinson et al. 1991). Subsequently, the principles outlined in ROTHC have been adopted in various other models including CENTURY (Parton et al. 1987), SOCARATES (Kirschbaum et al. 2001), Soil Carbon Manager (Seeliger 1998), GRAZPLAN (Moore et al. 1997), Sustainable Grazing System Pasture Model (Johnson et al. 2003), APSIM (McCown et al. 1996), Carbon Accounting Model for Forests, CAMF (Richards and Evans 2000a), Carbon Accounting Model for Agriculture, CAMAg (Richards and Evans 2000b) and FullCAM (Richards 2001).

In ROTHC four active and one inactive soil carbon fractions are used (Coleman and Jenkinson 1999). The four active pools are: decomposable plant materials (DPM), resistant plant materials (RPM), microbial biomass (BIO) and Humified organic matter (HUM). The inactive fraction is referred to as inert organic matter (IOM). Because the clay content of the soil plays an important role in protecting soil carbon from microbial decomposition (Tisdall and Oades 1982), ROTHC modifies the proportion of carbon that goes to the microbial biomass and humified organic matter pools according to the clay content of the soil. Thus the microbial biomass pool is divided into two, unprotected (BIO_U) and protected (BIO_P), where the protected pool refers to the pool protected from decomposition due to physical coating by clay.

One useful model is Soil Carbon Manager (Seeliger 1998), which predicts rates of soil carbon accumulation under different management practices (see Figure 16). Predictions were obtained by running Soil Carbon Manager with an initial soil carbon content set at 0.9 per cent for soils containing 10 per cent and 30 per cent clay with measured annual rainfall (mm) obtained at Merredin over the period 1901–2005. The management strategies examined included continuous pasture with and without grazing and a four year rotation of three wheat crops followed by one grain legume crop with and without stubble removed. The nitrogen input when wheat was grown was set at 50 kg N/ha.

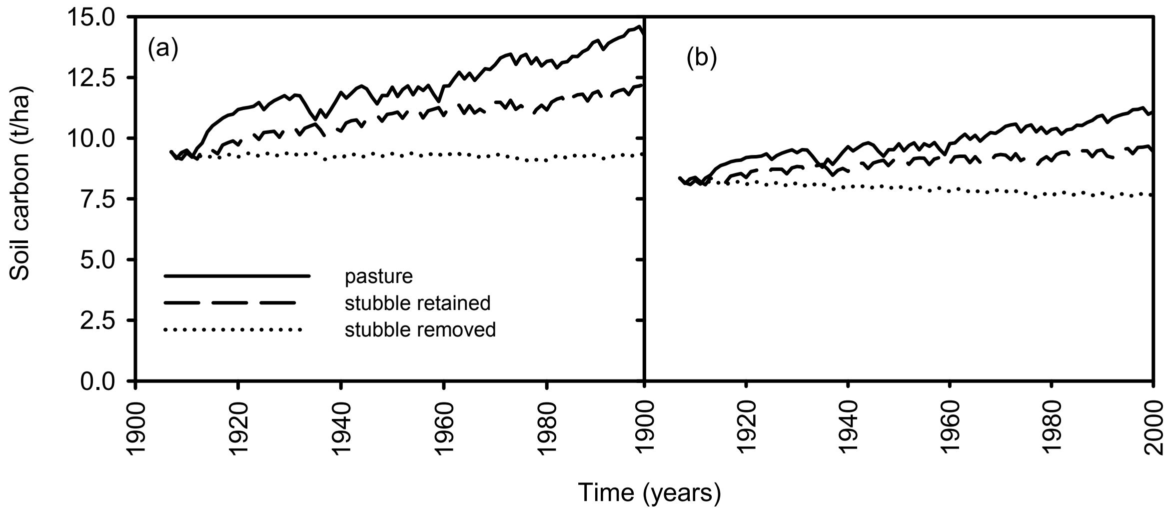

Figure 16 **Soil carbon (per cent) level predicted by Soil Carbon Manager for soils with (a) 30 per cent and (b) 10 per cent clay content for various management treatments**

The impact of management practices on soil carbon for the two soil types over time is presented in Figure 16. At the end of the study period the soils on average were predicted to contain 0.04 per cent DPM, 7 per cent RPM, 64 per cent, HUM and 24 per cent IOM. The major difference between the soils was the amount of soil carbon contained in the BIO_P pool. The BIO_P pool of the soil with 30 per cent clay accounted for 10 per cent of soil carbon compared to the soil with 10 per cent clay, which contained 2 per cent of soil carbon in the BIO_P. Burning of the stubble resulted in a greater percentage of soil carbon in the inert soil pool for both soils.

Table 12 **Soil carbon (t C/ha and %) fractions predicted by Soil Carbon Manager after 104 years using observed annual rainfall**

	Soil type and management practice	BIO_U	BIO_P	DPM	RPM	HUM	Inert	Total
(a)	**30% soil clay content**				**(t C/ha)**			
	Pasture heavily grazed	0.01	1.6	0.01	1.0	9.2	2.9	11.9
	Pasture not grazed	0.01	2.4	0.02	1.5	11.8	2.9	14.4
	Crop burnt	0.00	0.6	0.00	0.3	5.9	2.9	8.4
	Crop retained	0.01	1.3	0.00	0.8	9.8	2.9	11.8
					(% of total)			
	Pasture heavily grazed	0.05	11.0	0.07	6.7	62.3	19.9	
	Pasture not grazed	0.06	12.9	0.08	8.0	63.4	15.6	
	Crop burnt	0.03	6.2	0.01	3.4	60.4	29.9	
	Crop retained	0.04	9.1	0.02	5.2	66.0	19.7	
(b)	**10% soil clay content**				**(t C/ha)**			
	Pasture heavily grazed	0.00	0.3	0.01	1.0	7.6	2.9	14.7
	Pasture not grazed	0.01	0.4	0.02	1.5	9.6	2.9	18.7
	Crop burnt	0.00	0.1	0.00	0.3	5.0	2.9	9.8
	Crop retained	0.00	0.2	0.00	0.8	7.8	2.9	14.9
					(% of total)			
	Pasture heavily grazed	0.03	2.4	0.09	8.4	64.4	24.7	
	Pasture not grazed	0.04	2.9	0.11	10.3	66.4	20.3	
	Crop burnt	0.01	1.3	0.01	4.0	59.7	34.9	
	Crop retained	0.02	2.0	0.003	6.6	66.5	24.9	

Soil Carbon Manager predicted rates of change in soil carbon levels for soil with a 30 per cent clay content, to range from 0.053 t C/ha/year for the pasture not grazed to -0.002 t C/ha/year when stubble is burnt. Lower rates of soil carbon accumulation were predicted for the soil with a 10 per cent clay content with predicted rates of accumulation ranging from 0.029 t C/ha/year for the pasture not grazed to –0.008 t C/ha/year when stubble is burnt.

Grain yield predictions and hence carbon inputs in Soil Organic Carbon Manager are achieved using the French and Shultz (1984) relationship. This relationship defines wheat grain yield potential according to May–October rainfall with a water use efficiency of 20 kg/mm/ha. However, Abrecht et al. (2006) have shown that seasonal variation in wheat yield is due to both season conditions and agronomy practices, with time of sowing being the most influential practice. Hence, Soil Organic Carbon manager will tend to over-predict soil carbon accumulation. Campbell et al. (2007) observed that models which predict yield or operate using measured yield, more actually predict changes in soil carbon.

6.8 Soil structure

The major advantage of maintaining crop residues on the soil surface as mulch is that it allows for better water infiltration (Unger, 1994). The benefits of reduced tillage and retention of stubble to the soil structure of a hard setting red loam was examined by Wilson (1995) and Blackwell (2000) in an experiment near Mullewa. Stubble treatments consisted of stubble burnt (SB) and stubble retained (SR), while tillage treatments consisted of the use of wide points referred to as reduced tillage (RT) or discs referred to as no tillage (NT). Wheat was grown in 1992–1995 followed by Albus lupins (1996), canola (1997), wheat (1998) and lupins (1999).

The benefits of stubble retention were observed in the second year of the trial (Figure 17). No-tillage treatments were observed to increase grain yield in the fifth year (1996), when the combined use of stubble retention and discs (SRNT) more than doubled Albus lupin grain yield compared to stubble burnt and reduce tillage (SBRT) treatment. This effect was related to water logging early in the growing season arising from 147 mm of July rainfall. The stubble burnt and reduced tillage treatment had more surface ponding and plant death leading to reduced yield compared to the stubble retained no-tillage treatment.

Soil carbon was higher for the stubble retained no-tillage treatment (Table 13). Unsaturated hydraulic conductivity, measured in 1995, was not related to the water logging observed in 1996. In contrast, time to ponding, measured after 1996 using a rainfall simulator supplying 40 mm/h of artificial rainfall, showed the least disturbed treatments allowed more rapid surface drainage and longer times to ponding compared to the most disturbed treatment. In 1999, at the end of the experiment, the hard setting index of the less cultivated treatments with retained stubble was 63 per cent less than under the most cultivated stubble burnt treatments. Previous observations have shown the hard setting index to give the highest correlation with the time to ponding (Blackwell 2000).

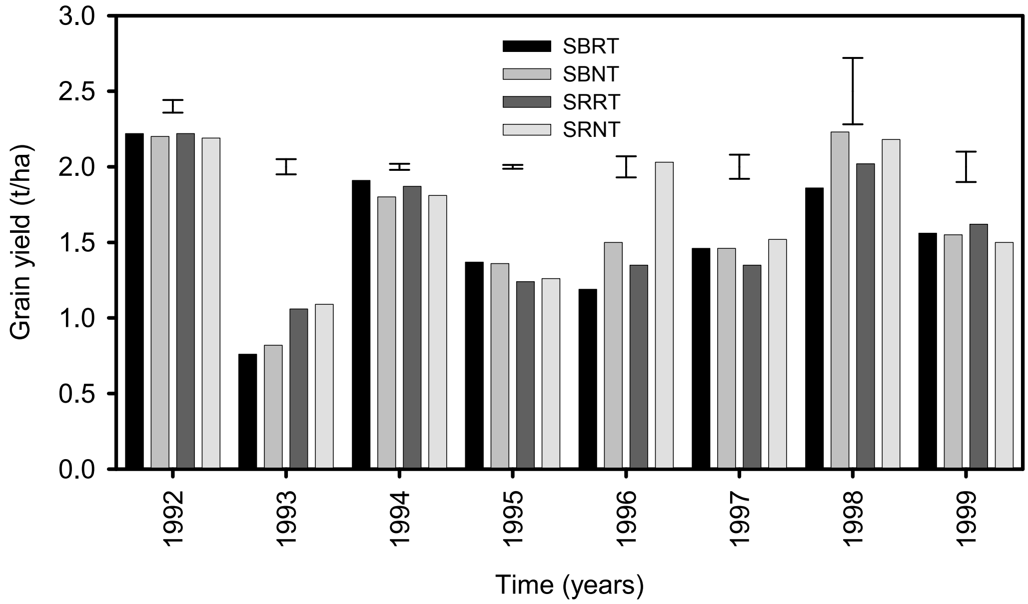

Figure 17 **Grain yield (t/ha) observed for stubble burnt (SB) or stubble retained (SR) for the cultivation treatments wide points (RT) and discs (NT)**

Table 13 **Soil properties measured in treatments receiving the greatest difference in amount of cultivation**

Measurement	System	Year			
		1992	1994	1996	1999
Soil carbon (%)	SBRT*	0.73	0.68	0.67	0.77
	SRNT	0.71	0.71	0.79	0.82
Unsaturated K (mm/h)	SBRT*	4.90	3.20		
	SRNT	8.40	3.10		
Hard setting index (kPa)	SBRT*	1.53	1.85	1.56	1.04
	SRNT	1.51	1.80	0.47	0.38
Time to pond (minutes at 40 mm/hour)	SBRT*			5.50	6.20
	SRNT			9.00	12.00

* SWB treatment received an additional cultivation before seeding.

6.8.1 Greenhouse gas emissions

West and Marland (2002) estimated the overall impact of agricultural practices on atmospheric carbon dioxide by conducting a full carbon cycle analysis. This analysis included:

- emissions associated with agricultural practices
- effect of agricultural practices on productivity and land-use change
- effect of land-use change on net carbon flux
- a comparison to baseline value to estimate relative net carbon flux.

Emission of carbon dioxide from agriculture is generated from three sources: machinery used for cultivating the land, the production and application of fertilisers and pesticides, and soil carbon oxidised following soil disturbance (West and Marland 2002). The amount of soil carbon oxidised is largely dependent on the tillage practice. The amount of fertiliser and pesticide applied varies among crop types, crop rotations and tillage practices.

West and Marland (2002) compared carbon dioxide emission from a conventional tillage system using a mouldbord plough, a reduced tillage system using discs or chisels and a no-illage system which leaves the soil undisturbed. Table 14 illustrates the carbon balance obtained under conventional tillage and no tillage. Compared to conventional tillage systems, a no-tillage system was found to sequester 337±108 kg C/ha/yr more C to a sampling depth of 30 cm. In contrast, the difference between the ability of reduced tillage and no tillage systems to sequester carbon was insignificant. This data was derived from the US Department of Energy's Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystem's database of 76 long-term soil carbon experiments. Lower carbon dioxide emissions due to the operation of farm machinery were calculated for the no-tillage system (23 kg C/ha/yr) compared to the conventional tillage system (69 kg C/ha/yr), while higher carbon dioxide emissions due to agricultural inputs were calculated for the no-tillage system (114 kg C/ha/yr) compared to the conventional tillage system (99 kg C/ha/yr).

Table 14 **Average net carbon flux for US agriculture with changed tillage practices. Negative and positive values indicate reduction and addition to atmospheric carbon pool respectively (West and Marland 2002)**

	Conventional tillage (kg C/ha/yr)	No-tillage (kg C/ha/yr)
C sequestration in soil	0	–337
C emission from machinery	+69	+23
C emissions from agricultural inputs	+99	+114
Net C flux	+168	–200
Relative net C flux*	0	–368

* Relative net C flux represents the difference between the net C fluxes of conventional tillage system and no tillage system.

West and Post (2002) analysed data obtained from 67 long-term agricultural experiments, consisting of 276 paired treatments, and concluded that conversion of conventional tillage to no-tillage resulted in a higher rate of sequestration (570 ±140 kg C/ha/year). Crop rotation was found to have a positive impact on sequestration rates under continuous corn but no sequestration under a corn–soybean rotation.

Carbon sequestration under different tillage practices has been traditionally studied by conducting long-term tillage experiments and measuring the impact of different treatments on soil carbon content. Often the impact has been measured using shallow depths of the soil profile, less than 30 cm, as conducted by West and Post (2002). Baker et al. (2007) however, argue that differences in soil heat flux, soil strength, bulk density and the mulching effect of stubble between the two tillage systems will result in differences in root distribution within the soil profile. This argument is supported by Qin et al. (2005) who observed that no tillage resulted in higher root length density in the 0–5 cm layer, but lower root length densities in deeper layers. VandenBygaart et al. (2003) found no tillage gave higher soil carbon content for experiments when soil sampling depth was less than 30 cm but lower soil carbon content when the sampling depth was greater than 30 cm. Gal et al. (2007) calculated a no-tillage treatment to result in 23 t C/ha more soil carbon than a plough treatment when measured to a depth of 30 cm, but only 10 t C/ha more soil carbon when measured to a depth of 100 cm. Finally, Powlson and Jenkinson (1981) found soil carbon content was the same under long-erm ploughing and no-tillage cereal plots when sampled to 40 cm. It was concluded that no-tillage has little effect on soil carbon content other than altering its distribution in the profile. This observation is supported by Hamblin et al. (1982) who observed root distribution showed a very marked inflection around 20 cm. It was concluded that the more favourable seedbed and surface conditions provided by ploughing were responsible for the more rapid wetting up of that soil and its resulting lower soil-strength and deeper early penetration of wheat roots producing higher grain yields.

New experimental techniques are becoming available where changes in soil carbon can in principle be inferred from continuous measurement provided other carbon additions or losses (e.g. harvested grain) are properly credited (Baldocchi 2003). Using this technique Baker and Griffis (2005) found both conventional tillage and strip tillage systems resulted in small net gains of carbon over the two-year period. Similarly, Verma et al. (2005) measured net ecosystem carbon dioxide exchange for two years in three adjacent fields in Nebraska. Though there were differences among systems in gross primary productivity and yield, the net carbon balance was essentially zero for all fields.

In addition to carbon dioxide, nitrous oxide is also released by soils. Nitrous oxide is derived from two separate processes, nitrification and denitrification, both of which are highly dependent on soil conditions. Nitrous oxide emissions are reduced by limiting the occurrence of water logging and compaction. In most cases practices that address water logging and compaction will be linked to improvements in soil structure leading to better water infiltration and storage. Time to ponding has important implications on amounts of nitrous oxide emissions. Blackwell (2000) observed increased times to ponding for the stubble retained no tillage treatment compared to the stubble burnt reduced tillage treatment.

Nitrous oxide emission measured over twelve months gave 0.09 kg N/ha for no nitrogen fertiliser treatment and 0.11 for applied nitrogen fertiliser treatment (Barton et al. 2007). This difference between nitrogen fertiliser treatments was not significant. Highest rates of nitrous oxide emissions of 7.3 g N/ha/day occurred following a summer rainfall event in the applied nitrogen fertiliser treatment. This compares to 4.8 g N/ha/day nitrous oxide emission for the no nitrogen fertiliser treatment. Rates of emission were also elevated immediately following planting. These losses coincided with high soil water contents, high inorganic nitrogen concentrations and high soil temperature in the case of the summer rainfall event.

Chatskikh and Olesen (2007) observed both carbon dioxide and nitrous oxide emissions to decrease with a reduction in tillage. Carbon dioxide emissions following conventional tillage of 40 kg C/day were 25 per cent higher than carbon dioxide emissions measured for the direct drill treatment. Similarly, nitrous oxide emission following conventional tillage of 0.89 kg N/ha or 7.9 g N/day were about twice that of direct drill treatment. However, spring barley grain yields were reduced by 27 per cent for direct drill compared to conventional tillage treatments. Measurements of soil mineral nitrogen at sowing showed no difference between the treatments, and thus could not explain the differences in nitrous oxide emissions and crop nitrogen uptake. It is likely that tillage affects carbon dioxide emissions, nitrous oxide emissions and crop growth through different processes.

Adviento-Borbe et al. (2007) examined the net global warming potential (GWP) in four agricultural systems: recommended best management practice continuous maize, intensive management continuous maize, recommended best management practice maize–soybean rotation and intensive management maize–soybean rotation. No tillage was used across all treatments. All four cropping systems were net sources of greenhouse gas emissions. However, due to increased soil C sequestration, continuous maize systems had a lower GWP than maize–soybean systems. It is often thought that intensification of agricultural systems will result in increased greenhouse gas emissions. However the results showed that intensive management did not cause a significant increase in net global warming potential.

Seasonal conditions, management practices and irrigation were responsible for variation in both carbon dioxide and nitrous oxide emissions. There were greater residue inputs in the two continuous maize systems compared to the maize–soybean rotation, resulting in an increase in soil carbon content under the continuous maize and a decline in soil carbon content under the maize–soybean rotation. Converting maize grain to ethanol in the two continuous maize systems resulted in a net reduction in life cycle greenhouse gas emissions of maize ethanol relative to petrol-based gasoline by 33–38 per cent.

7. Soil fertility

7.1 Introduction

Insufficient soil availability of macro-nutrients nitrogen (N), sulfur (S), potassium (K), phosphorus (P) and micro-nutrients copper (Cu) and zinc (Zn) have the potential to reduce crop and pasture growth in the region (Moore 2001). Calcium (Ca), magnesium (Mg), manganese (Mn) and molybdenum (Mo) are important nutrients but are not considered to have an impact on plant production.

Production or yield of crops and pastures can be expressed in terms of soil yield, managed yield and potential yield. Soil yield represents the production obtained from the soil at a given soil nutrient status. Managed yield is the production obtained from the soil plus inputs of nutrient determined by farmer's decisions. Potential yield is determined by the environmental limitations of water, temperature and solar radiation.

The processes associated with nutrient supply and plant uptake are complex. A great deal of research has been conducted to determine the capacity of the soil to supply nutrients to the growing plant and the results can be expressed as a number of relationships to calculate soil limitation and the amount of fertiliser required to obtain an economically optimal yield.

Management of stubbles can impact on the amounts of nutrient recycled and on the processes of mineralisation and immobilisation. Mineralisation is the process whereby organic N, S and P are converted to inorganic N, S and P. Immobilisation is the opposite process, whereby inorganic N, S and P are converted to organic N, S and P. When the nutrient is in the inorganic form it can be taken up by plants. The degree of stubble impact on the supply of inorganic nutrients is dependent on the amount of stubble, the carbon:nutrient ratio of the stubble, the form (inorganic or organic) within the stubble and the quality and degree of incorporation into the soil.

7.2 Measurement

7.2.1 Nitrogen

The availability to the plant of soil nitrogen (ST_N) is determined by several plant, soil and climatic variables. Currently ST_N is predicted based on the level of soil inorganic pools (SN_n), plant residue organic nitrogen (RON) and soil organic nitrogen (SON) (Bowden and Burgess 1993; Diggle and Bowden 2003). Soil inorganic nitrogen (nitrate and ammonium) is measured using 2 M potassium chloride as the extracting solution. It is shaken for 1 hour and the filtrate measured calorimetrically (Rayment and Higginson 1992). The ST_N is the sum of the different sources of soil nitrogen multiplied by their respective availabilities as presented in Equation 3.

Equation 3 $ST_N = (k_{SN} \times SN_n) + (k_{FN} \times FN_n) + (k_{RON} \times RON_{Ln}) + (k_{SON} \times SON)$

Where:

- SN_n represents soil inorganic nitrogen where subscript n is either NO_3 for nitrate or NH_4 for ammonium
- FN_n represents applied nitrogen fertiliser
- RON_{Ln} represents residue organic nitrogen where the subscript n is either u for lupin, f for field peas or p for pastures
- SON represents soil organic nitrogen pool

- k represents availability indexes for nitrogen sources where the subscript SN and FN values are related to leakage, RON ranges between 0.3 and 0.7 and SON ranges between 0.02 and 0.03 (Bowden and Burgess 1993).

Nitrogen uptake (N_{UP}) is a function of plant available soil nitrogen (ST_N) and maximum N uptake (N_{max}), as determined by Equation 4 (Burgess et al. 1991; Adams et al. 2000).

Equation 4 $N_{UP} = N_{max} \times \tanh(ST_N/N_{max})$

Where:

- N_{max} represent the maximum N uptake by the plant and is equal to $z_N \times PY$ (kg/ha)
- z_N is a constant and is equal to 0.06 for cereals and 0.07 for canola
- PY is potential yield (kg/ha)
- ST_N is plant available soil nitrogen (kg/ha).

Soil yield (SY_N) obtained at a level of plant available nitrogen (ST_N) is predicted as a function of potential yield and N uptake using Equation 5.

Equation 5 $SY_N = PY \times [(2 \times N_{up}/(g_N \times PY))–(N_{up}/(g_N \times PY))^2]$ (Angus et al. 1993)

Where:

- gN is a constant and is equal to 0.04 for cereals and 0.07 for canola
- N uptake (Nup) required to achieve maximum grain yield is given by gN x PY

Grain protein content (GP_N) obtained is a function of N uptake and potential yield as calculated by Equation 6.

Equation 6 $GP_N = 5.07 \times N_{UP} \times NHi \times PY \times KnHi/(KnHi \times PY \times N_{UP})$

Where:

- Value 5.07 is a protein conversion factor
- NHI = 0.80
- KnHI = 0.07.

Grain protein percentage ($GP_{N\%}$) content is calculated using Equation 7.

Equation 7 $GP_{N\%} = GP_N/SY_N \times 100$

7.2.2 Sulfur

Plant available soil sulfur (ST_S) is determined by the KCl_{40}–S soil test (Blair et al. 1991). KCl_{40}–S measures both the level of inorganic sulfate and a pool of labile organic sulfur which is mineralised over the growing season. A calibration curve has been developed for pastures over a range of soil types and climatic conditions (Anderson et al. 1994). The critical KCl_{40}–S test that gives YR_S of 0.9 was defined as 6.5 mg/kg. The relationship between ST_S or KCl_{40}-S extractable sulfur and YR_S for pasture is given in Equation 8 (Anderson et al. 1994).

Equation 8 $YR_S = 1.0 – (1.1 \times (\exp(–0.40 \times ST_S)))$

7.2.3 Phosphate

The Colwell P soil test is used to measure plant available phosphorus (ST_P) (Colwell 1963). Plant available phosphorus values are strongly influenced by the capacity of soil to sorb P (Barrow and Shaw 1976). In Western Australia, the capacity of the soil to sorb P is frequently

assessed using ammonium oxalate extractable iron commonly referred to as 'reactive Fe' (Schwertmann 1964) and the Phosphate Retention Index or PRI (Allen and Jeffery 1990). Moody and Bolland (2001) separated soils into six sorption classes based on reactive Fe and PRI (Table 15).

Table 15 **Phosphate retention defined by levels of reactive Fe and PRI with corresponding c coefficient and critical soil phosphorus test**

Phosphate Retention Class	Reactive Fe (μg Fe/g soil)	PRI	c coefficient	Critical ST_P (μg P/g soil)
Very very low	< 100	< 2	0.180	12–15
Very low	101–150	3–7	0.125	16–20
Low	151–400	7–35	0.100	21–25
Moderate	401–500	35–50	0.085	26–30
High	501–1000	51–100	0.070	31–35
Very high	> 1001	> 101	0.060	36–40

The relationship between plant available phosphorus (ST_P) or bicarbonate extractable phosphorus and yield ratio for phosphorus (YR_P) is given in Equation 9 (Moody and Bolland 2001).

Equation 9 $YR_P = 1.0 – (1.0 \times (\exp(–c \times ST_P)))$

7.2.4 Potassium

Bicarbonate extractable K (ST_K) is measured by the procedure of Colwell and Grove (1976). The critical ST_K or the soil test value which gives YR_K equal to 0.9 was defined as 35 mg/kg (Wong et al. 2000). The relationship between ST_K and YR_K is given in Equation 10 (Wong et al. 2000 modified by Bowden 2005).

Equation 10 $YR_K = 1.0 – (1.0 \times (\exp(–0.05 \times ST_K))$

7.3 Management implications

7.3.1 Wheat stubble

Stubbles vary markedly in their nutrient content depending on crop type, soil type, fertiliser history and season conditions. Thus stubble management practices will affect both long and short-term nutrient balances. Schultz and French (1976) measured the nutrient content of wheat stubble (Table 16). The amount of nutrients recycled in wheat stubbles is calculated from the nutrient concentration in the stubble and the quantity of that stubble. Using potassium as an example, in 3 t/ha of stubble the quantity recycled varies from 21 to 76 kg K/ha.

In the short term, the plant availability of nutrients in stubbles will be reduced by the fraction of the nutrient that becomes available to the plant in the growing season. This will be determined by the chemical form of nutrient in the stubble, whether inorganic or organic, and the way the stubble is managed.

Table 16 **Wheat stubble nutrient contents (kg/t and g/g) measured by Schultz and French (1976)**

Element	Units	Low	Mean	High
Nitrogen	kg/t	1.6	5.1	11.5
Phosphorus	kg/t	0.2	0.5	1.5
Potassium	kg/t	6.9	12.8	25.5
Sulphur	kg/t	0.8	1.3	2.1
Calcium	kg/t	1.0	1.8	3.8
Magnesium	kg/t	0.9	1.5	2.6
Copper	µg/g	3.0	6.0	12.0
Zinc	µg/g	3.0	7.0	27.0
Manganese	µg/g	16.0	41.0	78.0

Nutrients in the inorganic compounds (K) can be leached out of the stubble and into the soil in a plant-available form by a small amount of rain during December and January (Figure 18). In contrast, nutrients contained in organic compounds (N, P, S, Ca and trace elements) require micro-organisms to break down the stubble to convert the nutrients from their organic form to the inorganic form. The rate at which this happens varies markedly depending on environmental conditions, temperature and moisture, and how the retained stubble is managed. For example, if stubble is not incorporated into the soil the breakdown rate is slow. In contrast, if it is incorporated into the soil and conditions are warm and moist, then breakdown can be quite rapid.

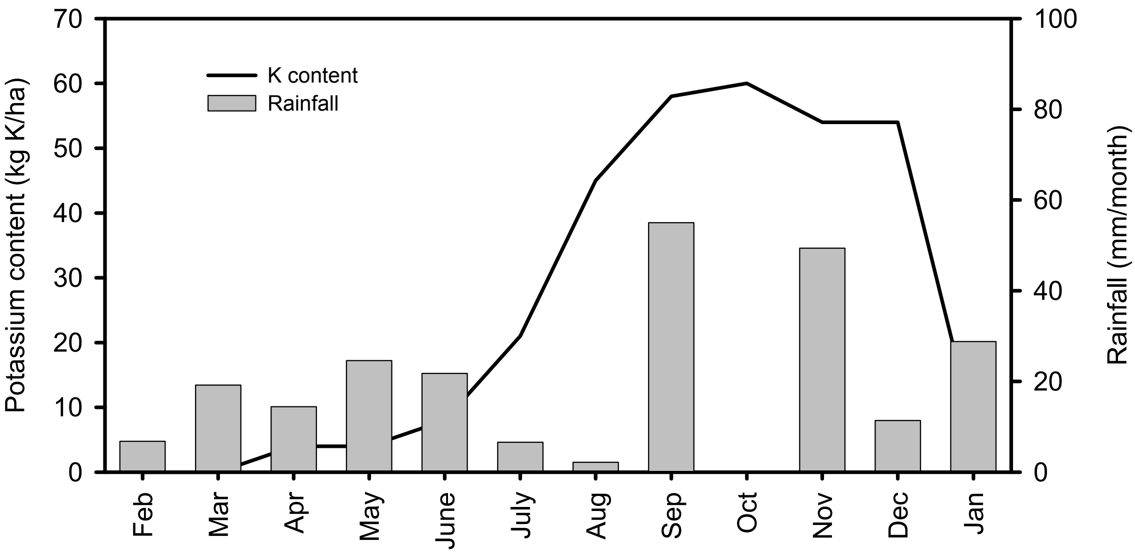

Figure 18 **Potassium prediction of K content of wheat biomass and stubble at Merredin in 2002 (Scanlan and Bowden 2005)**

When stubble is grazed, these breakdown processes are speeded up in the microbial action in the rumen. However nutrients are redistributed into concentrated urine and faeces zones, which render them less available to all but the adjacent plants.

When stubble is baled, all the nutrients in the baled stubble are removed. The timing of the baling operation can impact on the amount of nutrient removed because K can be leached out of the stubble before it is baled.

In most years 75 per cent of the K would be leach from the stubble prior to burning in April-May. When stubble is burnt, some nutrients (N and S) go off as gases while others form unavailable compounds in the ash. Nutrients in the ash can also lost as smoke or in subsequent wind erosion events. Burning with fire is an oxidation process that creates metal oxides of the cations. These oxides can have a rapid liming effect.

A number of assumptions are made when calculating the dollar value of nutrients retained by various stubble management options (Pluske and Bowden 2005). They include: no loss of ash after burning, no redistribution through grazing of nutrients in retained stubbles, 80 per cent of straw is baled, 50 per cent of straw is windrowed, the dollar value of nutrients, short and long-term plant availability of nutrient contained in the stubble and ash and per cent of nutrient lost through burning. The assumed values are presented in Table 17.

Table 17 **Nutrient costs, plant availability and loss through burning required to calculate short and long-term dollar values of stubble nutrients**

Nutrient	Nutrient costs ($/kg)*	Short term plant availability of stubble	Loss through burning	Short term plant availability of ash
N	1.34	0%	90%	80%
P	4.13	5%	5%	50%
K	2.19	75%	10%	80%
S	0.65	75%	25%	50%
Cu	23.94	0%	0%	30%
Zn	19.69	0%	0%	30%
Mn	6.66	0%	0%	30%
Lime	0.05	10%	0%	100%

* Based on August 2009 fertiliser prices

The short and long-term nutrient values ($/ha) calculated when stubble is retained, burnt, windrowed or baled are presented in Figure 19. Inherent in the calculations are the value of nutrient contents in wheat stubbles, the amount lost by each management practice and short-term plant availabilities of nutrient in stubble and ash.

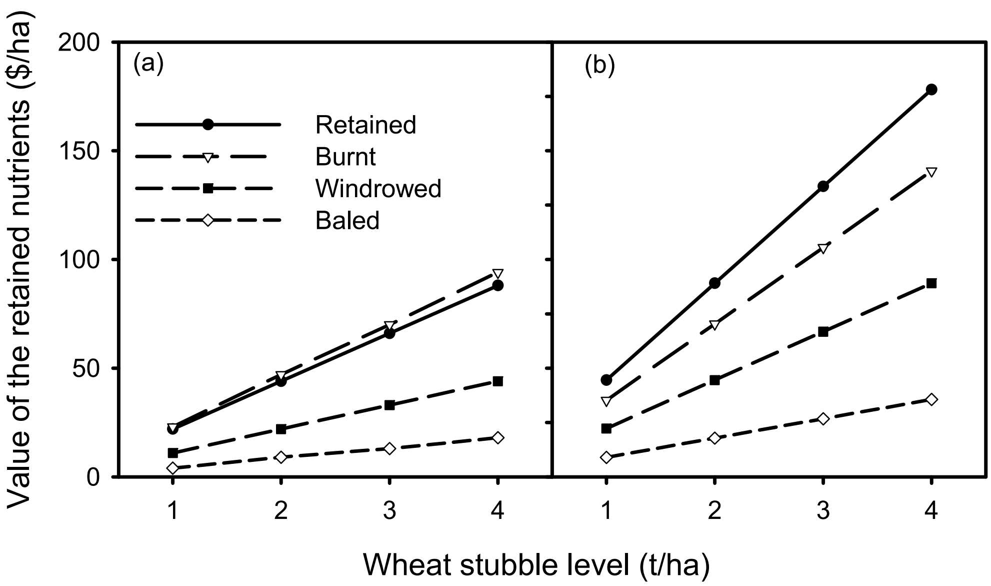

Figure 19 **Calculated dollar value ($/ha) of nutrient input from stubbles in the (a) short and (b) long term when the stubble is retained, burnt, windrowed or baled**

In the short-term burning of stubble compared to retaining stubble was calculated to give a small benefit, $1–$5/ha (Figure 19a). This is because burning improves the availability of all nutrients (Table 17) and the timing of the burning normally occurs after potassium has been leached out of the stubble. In contrast, in the long term all nutrients become available from the retained stubble. Hence, nutrients are lost when stubble is burnt compared to when stubble is retained. The dollar value of this loss is in the order of $9–$37/ha over the stubble range 1–4 t/ha (Figure 19b).

Compared to retaining stubble, the baling of stubble and the use of chaff carts, especially during or immediately after harvest, represents a large loss of nutrients both in the short term, a dollar value of $9–$35/ha (Figure 19a), and the long term $35–$140/ha (Figure 19b). For the practice to be profitable the dollars obtained from selling the baled straw needs to be greater than the value of the nutrients removed. At fertiliser prices for August 2009, profit will be made, in terms of nutrient removal, when the dollar value of the straw is greater than $35/t.

The C:N ratio in cereal decreases with plant age (Figure 20). In wheat with sufficient nitrogen supply, the nitrogen content at tillering is 7.4 per cent, giving a C:N ratio of 5.0. By flowering, the nitrogen content has dropped to 1.5 per cent, giving a C:N ratio of 27. At maturity nitrogen has been transferred from the leaves and stem to the grain, leaving the stubbles with a low nitrogen content of 0.6 per cent and producing a high C:N ratio of 70. In crops with poorer nitrogen supply this ratio can be as high as 150.

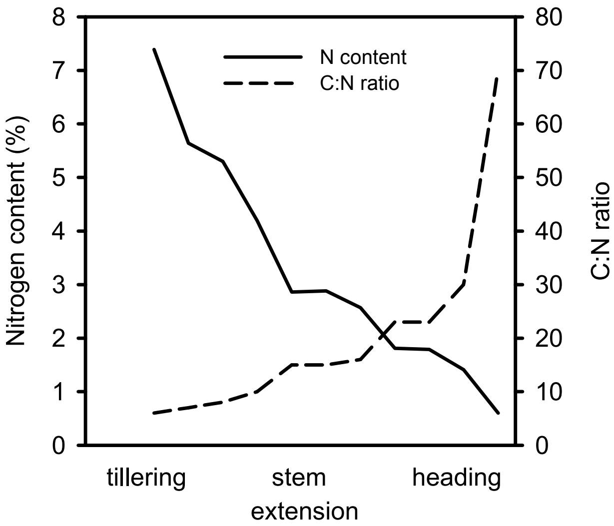

Figure 20 **Nitrogen content and C:N ratio of wheat plants at various growth stages**

The impact of wheat stubble retention on soil nitrogen availability is determined by the following factors:

- amount of stubble (kg/ha)
- proportion of wheat stubble removed by harvest procedure or grazing
- proportion of wheat stubble incorporated into the soil
- C:N ratio of stubble
- proportion of stubble C that is mineralised. This refers to the stubble carbon that is given off as carbon dioxide due to microbial decomposition. When stubble is incorporated into the soil, experiments have measured 50–70 per cent of wheat stubble carbon is respired by the micro-organisms.

Baldock (2005) combined these factors in a calculation that estimates the amount of nitrogen released from the previous year's stubble according to Equation 11. If a negative number is generated, then nitrogen is removed from the available pool during decomposition of the stubble. If the value is positive, a net release of nitrogen will occur.

$$\text{Net change in soil N (kg/ha)} = \left[\frac{\left(\text{Amount of stubble (kg/ha)}\right) \times \left(1 - \left(\text{Proportion of stubble removed}\right)\right) \times \left(\text{Stubble C content (\%)}\right)}{\text{Stubble C:N ratio}}\right] - \left[\frac{\left(\frac{\left(\text{Amount of stubble (kg/ha)}\right) \times \left(1 - \left(\text{Proportion of stubble removed}\right)\right) \times \left(\text{Stubble C content (\%)}\right)}{\text{Stubble C:N ratio}}\right) \times \left(1 - \left(\text{Proportion of stubble C that mineralises}\right)\right)}{\text{C:N ratio of the soil}}\right]$$

Equation 11

When cereal stubble is retained in the soil immobilisation of soil inorganic nitrogen occurs because soils have a C:N ratio of 10–15 while wheat stubble has a ratio of 70–150. That is, by retaining carbon from wheat stubble, the soil must supply inorganic nitrogen to maintain the soil C:N ratio. Hence, inorganic nitrogen is converted to organic nitrogen by the process referred to as immobilisation.

Photograph 5 (a) **Surface retained stubble in the inter-row of wheat sown at a site near Bruce Rock and (b) incorporation of stubble due to sowing across the previous wheat crop rows at a site near Mukinbudin**

Seeding system can be set up which allow the retention of stubble on the soil surface after seeding (Photograph 5). Thus the wheat stubble has reduced contact with the soil and is removed from the soil decomposition process. As a result an additional term that accounts for the amount of stubble incorporated should be included in the above calculation. The importance of the factor is illustrated a stubble management experiment conducted by Anderson (2007).

Wheat stubble levels (t/ha) are presented in Table 3. Equation 11 calculates different amounts of nitrogen immobilised due to the decomposition of various size fractions of wheat stubble (Table 18). Incorporation of the short stubble group resulted in immobilisation of up to 4 kg N/ha of soil inorganic nitrogen. Incorporation of both the short and medium stubble groups resulted in immobilisation of up to 16 kg N/ha of soil nitrogen. Finally, when all the stubble groups were incorporated into the soil, the nitrogen immobilised increased up to 45 kg N/ha.

Table 18 **Impact of incorporating various stubble fractions on predicted nitrogen immobilised (kg N/ha)**

Sites	Stubble management	Stubble retained (t/ha)	Calculated nitrogen immobilised (kg/ha) when stubble groups are incorporated in the soil		
			S	S + M	S +M+L
1	Windrowed	4.2	2	6	28
	Burnt	1.3	2	5	9
	Retained cut low	6.6	4	16	45
2	Windrowed	2.3	2	4	9
	Retained cut high	4.3	2	5	17
	Retained cut low	4.7	4	9	19
3	Windrowed	1.7	1	3	11
	Retained cut high	3.4	1	5	23
	Retained cut low	3.0	0	2	20

S is short fraction, M is medium and L is long stubble fractions

Nitrogen mineralisation was measured over three periods starting on 21 June and finishing 5 October during 2005 using the procedure of Anderson et al. (1998a). In the first period (21/06/05 to 28/07/05) after cultivation 5 kg N/ha was immobilised at the Bruce Rock site (Table 19). At the Mukinbudin site incorporation of stubble at seeding would have contributed to the higher level of immobilisation, 12 kg N/ha. Similar results have been observed by in an experiment conducted by Thompson (1992).

Table 19 **Net mineralisation (kg N/ha) measured from windrow treatment at two sites over three sample periods during 2005**

Period		Sites	
Start	Finish	Bruce Rock	Mukinbudin
21/06/2005	28/07/2005	–5.5	–12.0
29/07/2005	1/09/2005	10.6	4.2
5/09/2005	5/10/2005	27.7	23.2
Total		**32.8**	**15.4**

These observed values are a net result of mineralisation and immobilisation. Organic nitrogen may have been mineralised from soil organic matter during this time, thus the actual immobilisation measured at the sites may have been greater than the net measurements indicated. In subsequent sampling periods nitrogen mineralisation dominated at all sites. Rates of mineralisation were low (4–11 kg N/ha) over the August sample period due to lower temperatures compared to the September period (23–28 kg N/ha). Total net mineralisation ranged between 15 and 33 kg N/ha. The higher level of net mineralisation at the Bruce Rock site was due to the soil's higher soil carbon content of 1.2 per cent compared to 0.8 per cent at the Mukinbudin site.

The impact of immobilisation/mineralisation processes on wheat biomass production was small (Figure 21) because the soil profile contained relatively high levels of inorganic nitrogen (Figure 22). Also, wheat grain yield at the Mukinbudin site was relatively low (1.2–1.4 t/ha). The Bruce Rock site was badly affected by frost and the grain yield measured (0.8–1.0 t/ha) was below the potential yield (up to 2.5 t/ha) predicted from the biomass using a harvest index of 0.43.

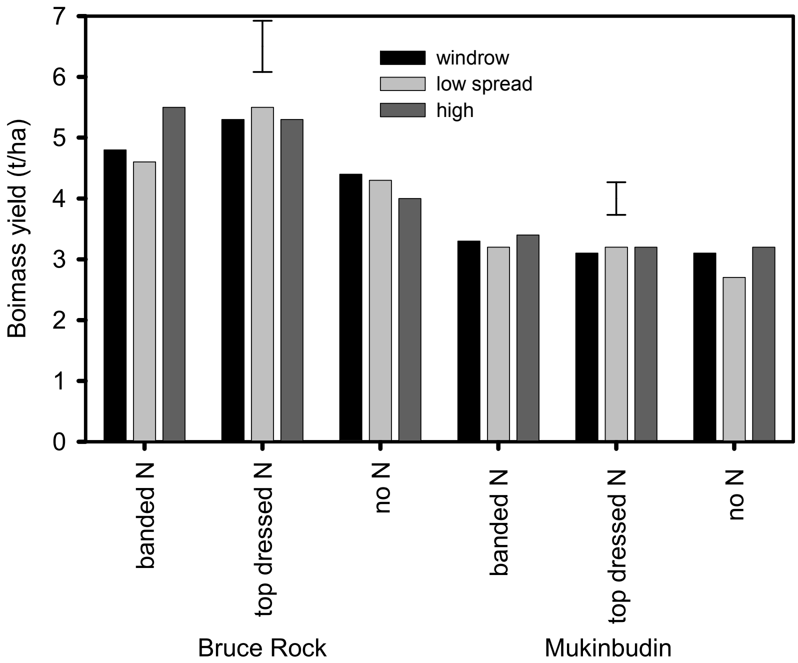

Figure 21 **Biomass yield (t/ha) at Bruce Rock and Mukinbudin sites, November 2005, with three stubble retention strategies (cut low and windrowed, cut low and spread, cut high and spread) and three nitrogen treatments (nil, banded and top dressed)**

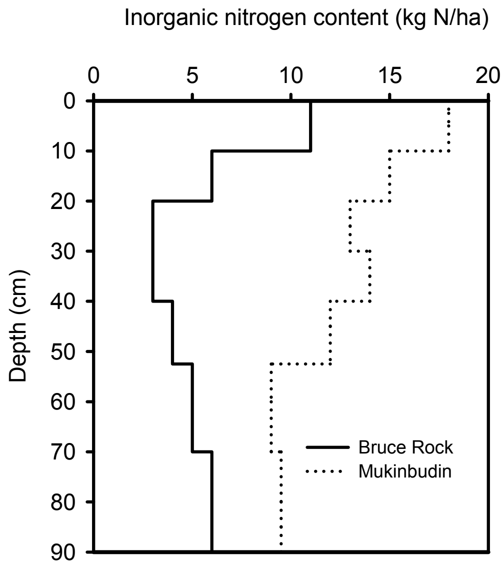

Figure 22 **Soil profiles of inorganic nitrogen content at Bruce Rock (77 kg N/ha) and Mukinbudin (131 kg N/ha)**

7.3.2 Legume stubble

Legume nitrogen inputs are derived from crop and pasture residues grown in the previous years. Diggle and Bowden (2003) refer to this organic nitrogen pool as residual organic nitrogen or RON. Residual organic nitrogen is derived from lupins (RON_{Lu}), field peas (RON_{Lf}) and pasture (RON_{Lp}). The amounts of residual organic nitrogen are derived using an estimate of biomass production and the nitrogen content of this biomass using equations 12 and 13.

Equation 12 $RON_{Lu\ and\ Lf}$ = legume grain yield x 1000*(N% biomass/HI – N % seed)

Equation 13 RON_{Lp} = 2/3 x pasture yield x 1000 x ((N% clover x % composition clover /100) + (N% capeweed x % composition capeweed/100) x (N% grass x (1 - (% clover + % cape weed)/100)))

Where:

- N% lupin seed = 5.00 and biomass 2.75
- N% field pea seed = 4.00 and biomass 2.50
- N% pasture components clover = 2.50, grass = 1.40 and cape weed = 6.50.

Variation in seasonal conditions, soil types and crop management can have a large impact on the components of Equation 12 and Equation 13. For example, seasonal and regional variation can result in lupin seed N ranging between 4.7 and 5.9 per cent and lupin biomass N ranging between 2.2 and 2.7 per cent (Anderson et al. 1988a; Dolling unpublished data).

The calculation k_{RON} x RON represents the amount of residual organic nitrogen mineralised over the growing season. The residual organic nitrogen fraction can remain in the soil for up to four years (Bowden and Burgess 1993). Hence, the size of the residual organic nitrogen pool after crops are harvested is estimated from both the previous year's input and the fraction carryover from previous years. Under no-till cropping systems 34 per cent of residual organic nitrogen is mineralised over the growing season, while with tillage this fraction increases to 50 per cent (Bowden and Burgess 1993).

8. Soil acidity

8.1 Introduction

Soil acidification is a natural process which is generally accelerated by agriculture (Helyar and Porter, 1989). Unfortunately, in many Australian agricultural areas, most acidification has occurred in subsoil (0.1–0.3 m) and can extend to below 0.8 m, especially where legumes are in rotation with wheat (Dolling and Porter 1994). Climatic conditions and agricultural practices that result in nitrate leaching (Anderson et al. 1998b) accelerate rates of soil acidification. Currently within the agriculture region of south-western Australia about 81 per cent of the surface soil layer and 25 per cent of the subsoil layers have soil pH less than 5.5 (Dolling et al. 2001).

Changes in soil pH are attributed to the generation and consumption of protons in the carbon and nitrogen cycle (Helyar and Porter 1989). Reduction in soil pH (soil acidification) occurs when excess cations and carboxylate anions are removed or nitrate is leached following denitrification (Kennedy 1992).

Cations taken up by plants (Ca^{2+}, Mg^{2+}, K^+, NH_4^+) maintain their oxidation state while some anions (NO_3^- and SO_4^{2-}) are reduced by plants and micro-organisms to form organic compounds. Examples of these reduction processes are:

- Nitrate reduction and assimilation: $R{\cdot}OH + NO_3^- + H^+ ==> R{\cdot}NH_2 + 2O_2$
- Sulfate reduction and assimilation: $R{\cdot}OH + SO_4^{2-} + 2H^+ ==> R{\cdot}SH + 3/2H_2O + 7/4O_2$

The plant maintains electroneutrality by excreting acidity or alkalinity, thus acidifying or alkalinising the rhizosphere. The type of charge excreted by crops is mainly controlled by the form of nitrogen (NH_4^+ or NO_3^-) taken up by plants. For example, in the case of legumes, because N is directly fixed from the atmosphere, the uptake of cations is normally much higher than the uptake of anions. This imbalance in nutrient uptake forces the plant to excrete protons into the rhizosphere, thus inducing soil acidification.

Plants take up more cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) relative to anions ($H_2PO_4^-$ SO_4^{2-}, Cl^-, NO_3^-) which results in an excess of positive charges. These are balanced externally by a net excretion of protons to the soil and internally by the synthesis of organic anions (Bolan et al. 1991). The exact relationship between proton excretion and organic anion accumulation is complicated and depends on the plant species and nitrogen nutrition (Jarvis and Robson 1983a, 1983b). Plants redistribute alkalinity within the soil profile by accumulating organic anions in residues deposited on the surface and the excretion of protons from roots into the deeper soil layers (Helyar and Porter 1989). These processes results in soil pH profiles characterised by alkaline surface soil horizon and acidified subsoils (Dolling and Porter 1994).

8.1.1 Carbon cycle

The effect of the carbon cycle on soil acidification can be broadly described as the balance between the formation and the decarboxylation of organic anions (Braschkat and Randall 2004). Decarboxylation refers to the loss to CO_2 from a carboxyl group or molecule (formula -COOH). The salts and anions of carboxylic acids are called carboxylates. The simplest series of carboxylic acids are the alkanoic acids, R-COOH, where R is hydrogen or an alkyl group. Compounds may also have two or more carboxylic acid groups per molecule. Carboxylic acids are widespread in nature. They are typically weak acids that partially dissociate into H^+ cations and $RCOO^-$ anions in aqueous solution.

With the decomposition of organic matter, the decarboxylation of organic anions consumes an equivalent amount of protons (Yan et al. 1996a, 1996b). Hence soil acidification due to the carbon cycle occurs both when the formation of organic anions exceeds their decarboxylation (when soil organic carbon is increasing), or when organic anions are removed through harvesting or grazing. Chan and Heenan (2005) found stubble retention was associated with decreased soil pH in both long and short-term experiments (Table 11).

Soil carbon has an important impact on soil acidification in agricultural systems where overall soil carbon levels are declining. As soil carbon levels decrease, there will be short-term gains, such that the overall rate of pH decline will be reduced. But as soil carbon levels fall to very low values (< 0.5 per cent), a more rapid pH decline will be observed. Slattery et al. (1998) estimates that for every 1 per cent loss in soil carbon in the 0–10 cm soil layer there is a loss in buffering capacity of about 3.9 cmol(+)/kg. These values are higher than the previously reported buffering capacities of 1.7 cmol(+)/kg (Kapland and Estes 1985) and 3.0 cmol(+)/kg (Chan et al. 1992).

8.1.2 Nitrogen cycle

The nitrogen cycle in agricultural systems is described in Figure 23. The key processes involved in this cycle are:

- Fixation—the conversion of atmospheric nitrogen to organic nitrogen associated with legumes.
- Mineralisation—the conversion of organic nitrogen to inorganic nitrogen by the activity of the soil micro-organisms.
- Leaching—the downward displacement of nitrate associated with the movement of water within the soil profile.
- Nitrification—the biological conversion of reduced nitrogen forms, ammonium and ammonia, to oxidised nitrogen forms, nitrite and nitrate.
- Uptake—the process of nitrogen uptake from the soil by the growing plant.

Nitrification is a key process in the nitrogen cycle because the current the cropping system of Western Australia uses large amount of nitrogen fertiliser. This nitrogen is applied mainly in the chemically reduced form which, upon biological oxidation (nitrification), generates and releases acidity (free protons; H^+) into the soil. The acid-forming nature of nitrogen fertilisers was firmly established by the pioneering work of W.H. Pierre in the late 1920s and early 1930s (Pierre, 1928).

When applied to the soil the various nitrogen fertilisers undergo the following reactions. These reactions illustrate how nitrification generates acidity or the release of protons:

- $NH_4NO_3 + 2\ O_2 ==> 2\ H^+ + 2\ NO_3^- + H_2O$ (ammonium nitrate)
- $(NH_2)_2CO + 4\ O_2 ==> 2\ H^+ + 2\ NO_3^- + H_2O + CO_2$ (urea)
- $NH_3 + 2\ O_2 ==> H^+ + NO_3^- + H_2O$ (ammonia)

For ammonium nitrate, urea, and anhydrous ammonia, proton production is stoichiometrically equal to nitrate production.

If nitrogen is supplied as organic nitrogen or biologically fixed nitrogen, which occurs in legumes, for every mole of NO_3^- leached out of the root zone, there is one mole of H^+ left in the soil, which induces acidification.

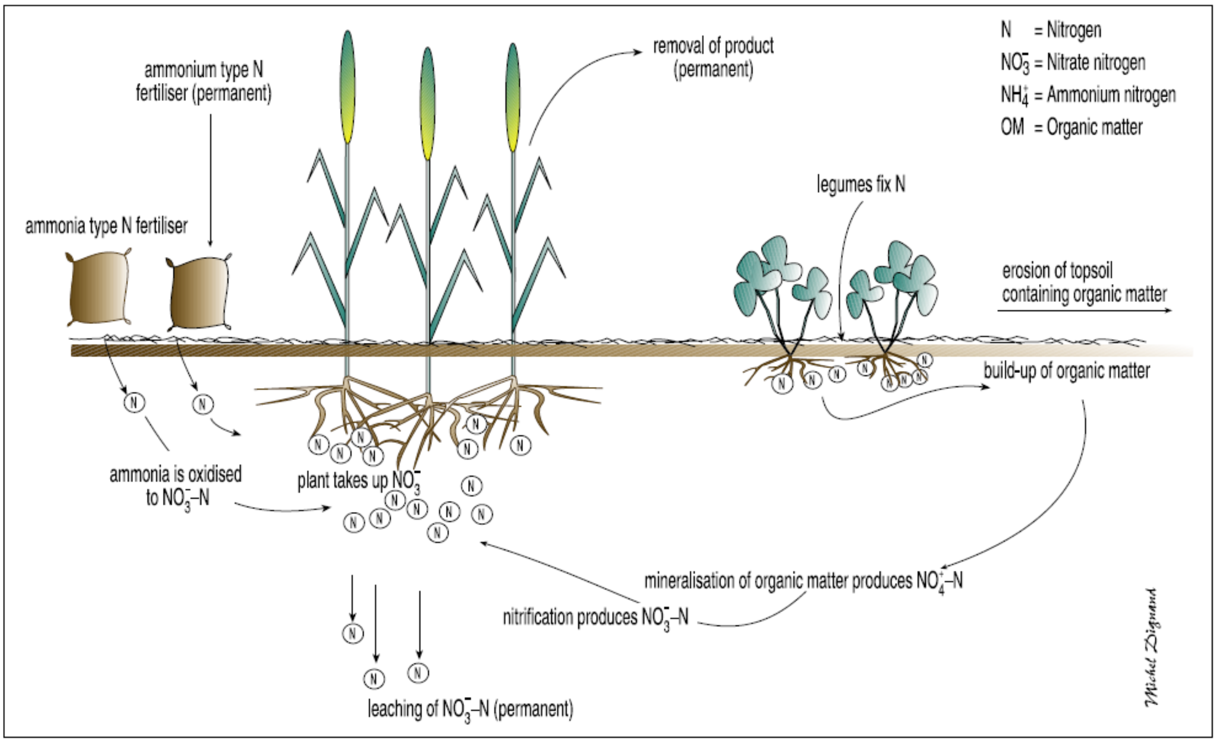

Figure 23 **Agricultural practices which result in soil acidification (Upjohn et al. 2005)**

8.1.3 Acidification rates

Slattery et al. (1998) observed a decline in both soil carbon and soil pH in a 15-year continuous cropping experiment. The main cause for the decline in soil pH was the removal of alkali in exported products in the carbon cycle and from the leaching of nitrate, leaving a net excess of protons in the surface layers of soil. Mean acidification rates were calculated to be 12.5 kmol(H+)/ha/year for continuous lupins and 4.1 kmol(H+)/ha/year for continuous wheat. The carbon cycle acid inputs into the two cropping systems were -5.7 kmol(H+)/ha/year for continuous lupins and –7.0 kmol(H+)/ha/year for continuous wheat, indicating that a substantial part of the acidification, which was probably due to nitrate leaching, was unaccounted for in both rotations.

The relative importance of product removal and nitrate leaching on rates of soil acidification will vary according to annual rainfall, soil types and land use. A detailed study on the relative impact of these factors on rates of acidification was conducted in the high rainfall zone, 450-750 mm (Anderson et al. 1998a, 1998b; Dolling 1999). The soil types were a deep yellow sand site located near Moora and a shallow yellow duplex site near Kojonup. In these studies, the highest rates of acidification occurred under wheat, 0.17–0.25 t $CaCO_3$ equivalents/ha/yr, with nitrate leaching accounting for > 95 per cent of the soil acidification. Under lupins, the rate of acidification ranges between 0.10–0.15 t $CaCO_3$/ha/yr on deep sands and 0.27–0.30 t $CaCO_3$/ha/yr on duplex soils, with nitrate leaching accounting for 80-90 per cent of the soil acidification. Acidification rates were lower under pastures (0.05-0.15 t $CaCO_3$/ha/yr) with nitrate leaching accounting for 0–60 per cent of the soil acidification. It is assumed in these calculations that 3.6 kg $CaCO_3$/ha is required to neutralise 1 kg N /ha leached.

In the medium and low rainfall zones less water and subsequently nitrate will be lost below the crops' rooting zone (Asseng et al. 2001; Fillery and Poulter 2006). In these zones, rates of acidification will be lower with a greater percentage accounted for by product removal

compared to the observations made by Anderson et al. (1998a, 1998b) and Dolling (1999). Also in these rainfall zones, variable seasonal conditions result in highly variable wheat grain yields of 0.0–4.0 t/ha (French and Schultz 1984), legume grain yield of both lupin 0.1-1.6 t/ha and field peas 0.3–1.6 t/ha (French 2005b) and pasture production 0.7–5.0 t/ha. Hence, it would be necessary to account for these variable yields when calculating acidifications rates.

Acidification rates due to annual product removal (t/ha), grain and biomass are presented in Table 20. Acidification rates due to removal of cereal grains are in the range 4–36 kg $CaCO_3$/ha. This is increased to 14–110 kg $CaCO_3$/ha when the wheat stubble is completely removed. Removal of legume plant material, grain and tops, has a greater potential to acidify the soil than cereal plant material when expressed on a per tonne basis. This is due to pasture legumes having a higher level of excess cations (114–147 cmol(+)/kg) compared to pasture grasses at 30–62 cmol(+)/kg (Braschkat and Randall 2004) and for canola, 30-49 cmol(+)/kg. However, grain legume yields are lower than cereal yields when expressed in terms of actual yields. Thus the acidity produced when legume material is removed is similar to the acidity produced when cereal grain is removed. An exception is when field pea stubble is removed, where the potential acidification effect is relatively high, 398 kg $CaCO_3$/ha.

Table 20 **The amount of CaCO3 (kg/ha) needed to neutralise the acidification caused by removal of produce (adapted from Fenton and Helyar 2000)**

Product	Equivalent $CaCO_3$ (kg/t)	Minimum value (t or sheep or lambs/ha)	Maximum value (t or sheep or lambs/ha)
Wheat grain	9	5	36
Wheat stubble	11	14	110
Barley grain	8	4	32
Barley stubble	8	10	80
Lupin grain	20	1	32
Lupin tops	60	9	382
Field peas grain	20	6	33
Field peas tops	60	48	396
Grass hay	25	18	305
Clover hay	40	28	488
Hay mixed grasses	30	21	366
Lucerne hay	70	49	490
Wool*	0.07	0.07	0.7
Meat*	0.02	0.02	0.2

* Additional acidification, for the majority of the paddock, occurs under set stocking with livestock. Pasture, which contains alkalinity, is removed during grazing and most of the alkalinity is deposited via dung and urine in areas where the livestock camp. The paddock becomes more acid, but the camps more alkaline.

8.2 Management implications

8.2.1 Stubble Management

In situations where the stubble is burnt in situ some alkalinity is lost but the alkalinity remaining is retuned to where it was produced. However, if the stubble is windrowed and then burnt there can be considerable redistribution of both nutrients and alkalinity. This corresponds to the depletion of nutrients and net acidification in the areas from which stubble has been removed. Brennan et al. (2004) observed the pH of coarse texture soils in the

0-10 cm soil layer could increase by as much as 0.7 of a pH unit under a burnt windrow because of the alkalinity being retuned and concentrated in that area. The concentration effect where chaff cart dumps are burnt in the paddocks is even greater than that for windrows. The end result can be a concentration of nutrients sufficient to have an adverse effect on the following crop. There can also be non-wetting induced by the prolonged high temperatures reached.

Incorporating stubble can increase the rate of nutrient cycling and can also help to reduce the acidification because stubbles (which are alkaline) are returned to where they were produced. Where the stubble is spread there is a similar return of the residue but the cycling of the nutrients and the alkalinity is generally slower. For the in situ grazed situation there can be a relocation of alkalinity in the form of faeces and urine into stock camps, while in the feedlot there can be removal of the feed from a paddock to the feedlot resulting in acidification of the paddock soil.

8.2.2 Lime application

Lime application is the main practice for correcting soil acidity. Currently lime is applied to the soil surface in a cropping system where the main cultivation practice is no-till or the use of knife points (D'Emden and Llewellyn 2006). Under this system, lime responses can take a number of years to develop as surface applied lime has a slow rate of dissolution and leaching (Whitten et al. 2000; Penny and Gazey 2001).

Lime sand consists of calcium carbonate ($CaCO_3$) contained in small sand particles. Calcium carbonate corrects soil acidity by reacting with the soil to produce bicarbonate ions. This process, a chemical reaction between the soil and the surface of the dissolving lime particle, is described by Equation 14 and Equation 15.

Equation 14 $CaCO_3 + 2H^+ = Ca^{2+} + H_2O + CO_2$

Equation 15 $CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$ (Stumm and Morgan 1996)

The bicarbonate ions produced then react with hydrogen ions to reduce the acidity of the soil.

The dissolution process of insoluble calcium phosphates (Kirk and Nye 1986ab; Anderson and Sale 1993) and lime materials (Ameloko 1983) has been well developed. In these models, lime dissolution rates are determined by:

- soil water
- particle size of the lime material
- concentration of ions at the dissolving surface
- concentration of ions in the soil solution
- buffer capacity of the soil
- the soil diffusion coefficients of the ions
- the interaction between dissolving particles.

Lime sources vary in quality and a system has been developed by Lime WA Inc. which makes it easier for farmers to compare products being offered by accredited suppliers. Lime suppliers operating under this code of practice provide accurate and up-to-date product information based on independent analysis from an approved testing laboratory. Lime quality—the ability of the lime material to increase soil pH—is determined by its particle size distribution (fineness) and neutralising value (NV). The standard code of practice laboratory test provides an analysis showing the NV of the bulk product as well as the NVs of each of the five particle size fractions.

- Particle size (fineness): The finer the product the greater the overall surface area and the faster it will react in the soil to neutralise acidity. Particle size distribution is based on the percentage of the lime sample in each size range after it has passed through five different sizes of sieving screens. Particles less than 0.5 mm neutralise soil acidity most quickly. Larger particles have a neutralising effect over a longer period.
- Neutralising value (NV): This value indicates the ability of lime to neutralise acidity. An NV is measured as a percentage for each of the five particle sizes. The higher the percentage, the greater the product's ability to neutralise acidity. An NV of 100 per cent indicates a product equivalent to pure calcium carbonate ($CaCO_3$) in its ability to neutralise acid.

A lime product with high ability to increase soil pH, will contain a high proportion of particles of less than 0.5 mm in size with high neutralising values (85–90 per cent).

An understanding of the chemical process of lime dissolution is required to develop management practices which will improve lime effectiveness. Once applied to the soil lime particles will begin to dissolve due to the presence of acidity or hydrogen ions (H^+) and water. Bicarbonate (HCO_3^-) and calcium (Ca^{2+}) ions are then released from the surface. This results in a concentration gradient between the surface of the dissolving particle and the soil solution. The concentration of HCO_3^- and calcium Ca^{2+} ions is higher at the particle surface than the soil solution, while the concentration of H^+ ions is lower at the particle surface. As a result H^+ ions will diffuse down the concentration towards the particle surface at the same time HCO_3^- and Ca^{2+} ions diffuse away from the dissolving particle surface.

A large difference in the concentration between the dissolving surface and the soil solution occurs when the soil solution levels of H^+ ions are high and Ca^{2+} ions are low. This will result in rapid dissolution of the lime particle. However, this rate of dissolution will only be maintained by the ability of the soil (the soil buffer capacity) to prevent an increase in the soil solution concentration. As the concentration in the soil solution begins to increase, the rate of lime dissolution decreases. In general, soils with low soil pH and high pH buffer capacity (pHBC) will give a steep concentration gradient between the soil and the dissolving particle surface, and the soil will dissolve more lime at a faster rate than soils with a high pH or low pHBC.

The soil pHBC of the 0–10 cm soil layer ($pHBC_{0–10\ cm}$) is related to the level of soil carbon (Raphael and Bowden unpublished data, Moore et al. 2001a).

Equation 16 $pHBC_{0–10\ cm} = 0.48 + 0.54$ soil carbon%, $r^2 = 0.91$

While the pHBC of the 10–20 cm soil layer ($pHBC_{10–20\ cm}$) is related to soil carbon and Al content:

Equation 17 $pHBC_{10–20\ cm} = 0.42 + 0.73$ soil carbon% + 0.40 Al, $r^2 = 0.82$

The soils of the eastern wheatbelt generally have low soil carbon levels, less than 1.0 per cent which gives the soil a low pHBC. This means the soils are poorly buffered to prevent pH decline due to acidification. Conversely soil acidity can be corrected by the application of relatively low rates of lime. However, application of lime to these soils in concentrated layers or bands reduces the soil's capacity to dissolve lime. In theory, the lime dissolution capacity (LDC) of soil can be calculated using soil pH, pHBC, cultivation depth, and bulk density (Equation 18). The developed equation is as follows (Anderson—Soil Management Calculator).

Equation 18 LDC = (7.5 – pH soil)*pHBC*BD*DC*CF

Where:

- soil pH 7.5 is the soil pH at which equilibrium is obtained between the soil and dissolving surface of the lime particle
- pH soil: measured in 0.01 M $CaCl_2$ solution
- pHBC is pH buffer capacity
- BD is bulk density
- DC is depth of cultivation
- CF which is equal to 0.05, is a conversion factor to convert units to t lime/ha.

Equation 18 illustrates how lime dissolution capacity is increased by mixing the lime with a greater amount of soil, achieved by increasing cultivation depth. The relationship between the capacity of the soil to dissolve lime, predicted by Equation 18, when lime is incorporated to different depths over a range of soil carbon is illustrated in Figure 24.

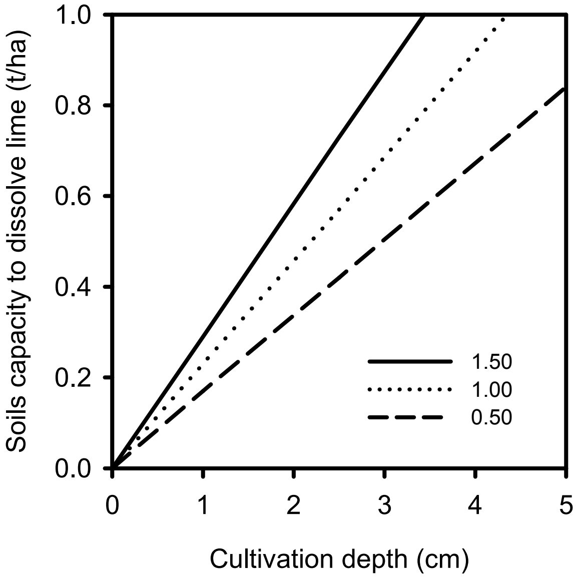

Figure 24 **The soil's initial capacity to dissolve lime (t/ha) as determined by cultivation depth (cm) and soil carbon content (per cent)**

The cost of applying lime in the eastern wheatbelt is high, about $46.50/ t of lime (August 2009). These costs are made up of $8.50/t for lime purchase at the pit, freight distance of 300 km, freight cost of $0.01/km and cost of spreading $8.00/t. Given this high outlay farmers need to maximise the effectiveness of the lime. Hence, in 2005 an experiment was set up to examine how the effectiveness of surface applied lime can be improved by surface cultivation (Anderson and Kidson 2006). Phosphorus sorption is influenced by soil pH, thus it was hypothesised that lime could improve phosphorus availability by reducing phosphate sorption.

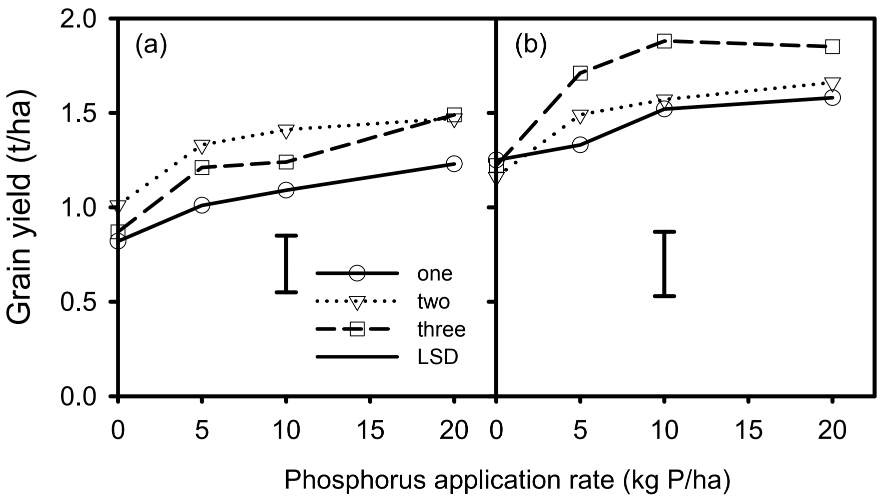

Figure 25 **Grain yield (t/ha) for (a) nil lime and (b) 2 t lime/ha for one (○), two (▽) and (□) pass with a scarifier set to a cultivation depth of 4 cm and banded phosphorus treatments**

Grain yield (t/ha) responded to lime, phosphorus and cultivation as presented in Figure 25. However, the interaction between cultivation and phosphorus application was not significant for the lime treatments. That is, the shape of the phosphorus response curves is the same for the different levels of cultivation. This was due to the placement of 50 per cent of the phosphorus fertiliser below the cultivation layer. The grain yield obtained for the nil phosphorus treatment was in the range 0.8–1.2 t/ha. The highest yield (1.9 t/ha) was obtained for the 2 t lime/ha with three cultivations and 10–20 kg P/ha. The response to these treatments was due to changes in soil chemical properties. These changes are illustrated by the comparison of the soil profile samples between the least productive treatments (0 t lime/ha, 1 cultivation, 0 kg P/ha) and the best treatments (2 t lime/ha, 3 cultivation 20 kg P/ha), measured after harvest (Table 21). The best plot had a higher soil pH and phosphorus levels and lower soluble Al and PRI levels within the soil layers.

Table 21 **Soil properties measured for treatments 0 t lime/ha, 1 cultivation and 0 kg P/ha compared to 2 t lime/ha, 3 cultivations and 20 kg P/ha. Soil samples were collected within seeding row**

Treatments sampled	Depth (cm)	Org C (%)	P (μg P/g soil)	PRI	pH	Al (μg Al/g soil)	△ pH	Dissolved lime (t/ha)
(1) 0 t lime/ha, and	0–10	0.6	6	20	4.1	0		
1 cultivation, and	10–20	0.4	2	48	4.0	20		
0 kg P/ha	20–30	0.3	3	69	4.1	16		
(2) 2 t lime/ha, and	0–10	0.8	22	10	4.8	0	0.70	0.47
3 cultivations, and	10–20	0.4	8	26	4.2	6	0.20	0.13
20 kg P/ha	20–30	0.4	10	63	4.1	8	0.00	

The calculated amount of lime dissolved as measured from the change in soil pH was 0.60 t/ha. This is less than the predicted lime dissolution capacity of 0.94 t/ha. This predicted capacity assumes an even mixing of lime into the cultivation layer. Perhaps greater lime dissolution could be achieved by using a more effective cultivation procedure, for example offset discs.

Initial interest in Australia and New Zealand in the use of the Kirk and Nye (1986a, 1986b) phosphate rock dissolution model was shown by Anderson and Sale (1993) and Tambunan (1992). However, there are limited potential environments in Australia where reactive phosphate rock will be effective as a phosphate fertiliser (Sale et al. 1997), and hence there has been no application of the Kirk and Nye model or the lime model developed by Ameloko (1983). Given the widespread occurrence of both surface and subsoil acidity, the need remains to obtain a better understanding of the dissolution of lime and the rate at which the released HCO_3^- ion diffuses into the soil.

9. Herbicides

9.1 Introduction

In conservation tillage systems herbicides are the main means of weed control. The high frequency of herbicide application in conservation tillage systems has resulted in the rapid development of herbicide resistance (D'Emden and Llewellyn 2006). Currently, most paddocks in many major cropping areas now contain herbicide resistant weed populations (Llewellyn and Powles 2001). This poses a significant challenge for the future. There is a need to develop and implement weed management strategies that are able to sustain long-term no-tillage practices that maintain soil conservation and production benefits but prevent the development of further resistance to herbicides (D'Emden and Llewellyn 2006).

Annual ryegrass is an important weed in Australia, infesting crops in a wide variety of soil types and climatic conditions (Gill 1996). Heap and Knight (1982) were the first to report annual ryegrass resistance to diclofop-methyl. Currently many biotypes of this weed have developed resistance to the majority of herbicides currently used (Preston et al. 1996), including glyphosate (Powles et al. 1998; Pratley et al. 1999). There is clearly a need for non-herbicidal options for the management of weeds (Wu et al. 1999).

Herbicide behaviour is governed by a variety of physical, chemical, biological and environmental processes, which are often complex and dynamic (Kookana et al. 1998). Herbicides can be grouped according to their properties. The most common division distinguishes non-ionic, weakly acidic or basic, hydrophobic or hydrophilic groups (see Table 22). These properties afford the herbicide a wide range of solubilities, volatilities, spectra of weeds they control and behaviour in the environment.

Table 22 **Herbicide classification based on chemical properties (Miller and Westra 2006 adapted from Weber 1991)**

Herbicide family	Commonly used herbicides
Non ionic	
Substituted ureas	Group C Karmex®
Dinitroanilines	Group D Trifluralin, Stomp®, Yield®
Thiocarbamates	Group E Avadex®, Eptam®
Chloroacetamides	Group K Dual®, Surpass®
Acidic	
Sulfonylureas	Group B Ally®, Glean®, Logran®
Imidazolinones	Group B Pursuit®
phenoxys/benzoics/picolinates	Group I 2,4-D, MCPA, Tordon®
Organic phosphorus	Group M Roundup®
Basic	
Triazines	Group C Atrazine, Bladex®, Gesagard®
Strongly basic	
Dipyridiniums	Group L Gramoxone, Diquat

Environmental processes governing herbicide behaviour include sorption, volatilisation, degradation and plant uptake. In addition there are surface run-off and leaching, each largely determined by herbicide properties and soil sorption capacity. Sorption and degradation are perhaps the two most important soil processes as the bulk of the applied herbicides are sorbed by organic and inorganic soil constituents, or undergo chemical and microbial

transformation or degradation. The relative importance of these processes varies with environmental conditions and herbicide properties and the net result is a complex interaction of herbicides in the environment that will impact on the ability of herbicides to control weeds.

Currently most of the work being done in Western Australia concentrates on the important issue of herbicide resistance. However, herbicide efficiency is largely determined by the processes that control their loss or breakdown and the interaction of these processes with tillage and stubble practices used by farmers.

9.2 Herbicide properties

This section attempts to summarise the main herbicide properties and environmental processes to determine how conservation farming impacts on the relative efficiency of trifluralin, one of the most commonly used herbicides in southern Australia.

9.2.1 Non ionic herbicides

Dinitroanilines

Trifluralin is a dinitroaniline belonging to the group D herbicide. The chemical structure of trifluralin or 2,6-dinitro-*N*,*N*-dipropyl-4-[trifluoromethyl] benzenamime is presented in Figure 26. It is a pre-emergence herbicide and has been used in agriculture since 1963. It is used to control mainly annual ryegrass in cereal crops and is applied immediately before seeding so that the seeding operation is used to incorporate it into the soil. Once incorporated in the soil it is protected from volatilisation loss and provides effective weed control. Its primary mode of action is in affecting the physiological processes associated with root growth and elongation.

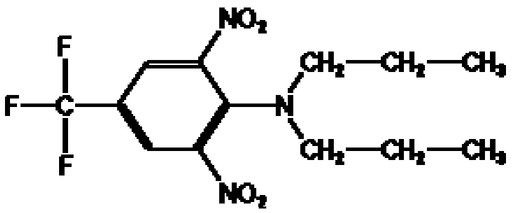

Figure 26 **The structural formula of trifluralin ($C_{13}H_{16}F_3N_3O_4$)**

Trifluralin is almost insoluble in water, with a solubility of 0.2 to 0.4 mg/L at 25 °C (Trifluralin 2006). It has a moderately high log octanol–water partition coefficient of 3^3. It is volatile, with a vapour pressure of 0.006 Pa at 20 °C and a Henry's law constant of 4.0–15.2 $Pa \cdot m^3 mol^{-1}$ (Grover et al. 1997).

Bedos et al. (2002) studied the fate of trifluralin applied to the soil surface. Volatilisation loss was measured as 29 per cent of the amount applied over 8 days with 17 per cent loss within the first 26 hours. Only 20 per cent of the applied trifluralin was recovered from the soil, giving a total recovery of 49 per cent. Possible reasons for this low recovery may be due to sampling errors or to the formation of bound residues which are not extractable (Grass et al. 1994) or trifluralin having degraded over the experimental period (Grover et al. 1997). Strynar et al. (2004) used an isotope technique to investigate the nature of soil-bound trifluralin residues. Trifluralin binding ranged between 10 and 53 per cent of the initial ^{14}C applied with a variety of mechanisms (covalent binding, adsorption, sequestration) involved.

The persistence of trifluralin in agricultural soils following incorporation is highly variable and depends on several factors such as depth of incorporation, soil moisture, soil temperature and soil carbon content. Jolly and Johnstone (1994) observed that trifluralin degradation is increased with increasing moisture and temperature. Measured degradation rates (half life in

days) range from 172–475 days at 10 °C, to 58–108 days at 20 °C and 41–73 days at 30 °C. The results also indicated the potential for long persistence of trifluralin in years of low rainfall.

Thiocarbamates

Thiocarbamates are group E herbicides which include Avadex® and Eptam®. These herbicides exhibit low to moderate water solubility, low to moderate soil retention, and high to very high volatility. Major atmospheric losses could occur if they were not immediately incorporated. As with the dinitroanilines, the rate of application is highly dependent on soil texture and soil carbon. A higher application rate is required on soils with higher clay and soil carbon. Soil texture, temperature and moisture also influence volatilisation: higher temperatures, coarser texture soils and soil moisture speed volatilisation. Depending on environmental conditions, the herbicides persist in soil from less than 10 to 30 days. The major means of loss is microbial decomposition.

Chloroacetamides

Chloroacetamides are group K herbicides and include Dual® and Surpass®. These herbicides exhibit moderate water solubility, low soil retention, and low to moderate volatility. As with the dinitroanilines and thiocarbamates, soil texture and soil carbon are important in determining application rates. Volatilisation rates are generally quite low. However, if no rainfall occurs within seven days following application, mechanical incorporation may be needed for adequate pre-emergence activity. Soil persistence ranges from less than 10 to 90 days. The major means of loss is microbial decomposition.

9.2.2 Substituted ureas

Substituted ureas are group C herbicides and include Karmex®. These herbicides exhibit very low to low water solubility, very low to moderate volatility, and low to high soil retention. They display a wide range of behaviours in soils, depending on texture, moisture and organic matter. They have short to moderate persistence and are degraded in soil by microorganisms.

9.2.3 Acidic herbicides

Phenoxys/Benzoics/Picolinates

Phenoxys/Benzoics/Picolinates are group I herbicides and include 2,4-D, MCPA and Tordon®. These compounds have high to very high acidity, low to high water solubility, and very low to moderate volatility. Water solubility and soil retention are both dependent on soil pH, with maximum soil sorption occurring under acid conditions. Sorption of 2,4-D is mainly by soil carbon with low sorption on both wheat and canola straw (Halabicki-Picton 2003; Farenhorst et al. 2006) (Figure 27). Persistence is generally short, with the exception of Tordon®, which exhibits long persistence. The major means of breakdown is microbial decomposition.

Sulfonylureas

Sulfonylureas are group B herbicides and include Logran®, Ally® and Glean®. These herbicides have moderate to high acidity and very low to low volatility. Herbicide retention ranges from very low to low, and water solubility from very low to high. Water solubility and soil retention are pH dependent. Retention is directly related to soil carbon content. Persistence ranges from short to long and is greatly influenced by environmental conditions. These herbicides appear to be more persistent under basic rather than acidic conditions. Both chemical and microbial decomposition are important processes of degradation.

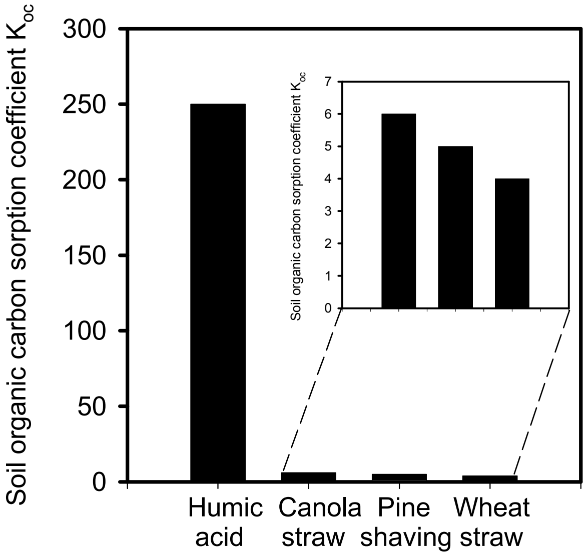

Figure 27 **The effect of soil carbon and carbon sources on sorption of 2,4-D (Halabicki-Picton 2003)**

Imidazolinones

Imidazolinones are group B herbicides and include Pursuit®. These compounds have high to very high acidity, moderate to high water solubility and very low volatility. Water solubility and soil retention depend on soil pH, with maximum soil sorption occurring under acid conditions. Soil retention is very low to low. Soil binding is greatly influenced by carbon content. Degradation occurs due to microbial decomposition and is favoured by warm, moist conditions.

Organic phosphorus

Organic phosphorus is a group M herbicide and includes Roundup®. These herbicides exhibit high acidity, high water solubility and very low volatility. They readily react with clay and metal oxides in soils to form insoluble iron, aluminium and calcium precipitates. As a result, they have very high soil retention and low soil mobility. Persistence is very short due to the formation of insoluble precipitates, making them biologically inactive upon contact with mineral soils.

9.2.4 Basic herbicides

These are group C herbicides and include atrazine, Bladex® and Gesagard®. The base strength of these herbicides ranges from very low to low. As a consequence, water solubility is dependent on soil pH. These herbicides range from low to moderate in solubility, very low to low in volatility, and low to high in soil retention. Soil retention is generally highest at low soil pH. Higher pH soils exhibit low herbicide binding and increase the potential for crop injury and leaching. Soil carbon content and clay mineral content are important in binding these herbicides to soil. Soil persistence ranges from very short to moderate. Chemical decay is a major avenue of herbicide degradation, with degradation dependent on soil pH. Degradation generally occurs faster under acidic than under neutral or basic conditions.

9.2.5 Strongly basic herbicides

These are group L herbicides and include dipyridiniums, gramoxone and diquat. These compounds exhibit very high base strength, very high water solubility, and very low volatility. They readily bind to the organic matter, with clay minerals chiefly responsible for this binding. Although they are very soluble in water, because of their cationic nature and their soil

retention properties, they are considered to be immobile in soil. The reported values for soil persistence are long to very long. However, when these herbicides are bound to the internal surfaces of clay minerals, the compounds are unavailable to microorganisms for decomposition. Thus, these compounds are found in a biologically inactive, yet stable form.

9.3 Environmental processes

9.3.1 Soil sorption

Sorption is the process by which herbicides bind to the soil particles. Sorption also regulates the accessibility of herbicides to their target organisms and their potential to reach non-target organisms. The sorption of non-ionic herbicides in Australian soil is directly related to soil carbon (Briggs 1981), while for basic (atrazine) and strongly basic (diquat) herbicides it is related to clay content (Kookana and Aylmore 1993).

Sorption potential of herbicides by soil carbon is related to their octanol:water partition coefficient (Kow). The Kow is a measure of the equilibrium concentration of a compound between octanol and water. A high Kow value indicates that a compound will partition into soil carbon rather than water. Measured values of Kow for organic chemicals range from 10^{-3} to 10^{7}. In terms of log Kow, this range is from –3 to 7. Log Kow is inversely related to the solubility of a compound in water.

Values of Kow can be considered to have some meaning in themselves, since they represent the tendency of a chemical to partition itself between an organic phase and an aqueous phase. Chemicals with low log Kow values (less than 1) are considered to be relatively hydrophilic or they have high water solubilities, small soil sorption coefficients, and small bio-concentration factors for aquatic life. Conversely, chemicals with high log Kow values (greater than 4) are very hydrophobic.

Log Kow is used in models to estimate plant and soil invertebrate bio-accumulation factors. In recent years Kow has become a key parameter in studies of the environmental fate of organic chemicals as it is related to water solubility, soil/sediment sorption coefficients, and bio-concentration factors for aquatic life.

Trifluralin has a log Kow ranging between 3.0 and 5.3 (Grover et al. 1997) so it can be strongly adsorbed by soil carbon. Soil carbon and clays can have pH-dependent charges and result in their sorption capacity changing with pH. Agronomic management practices such as liming and fertilisation can result in relatively abrupt changes in soil pH and consequently affect the behaviour of trifluralin applied to soils.

9.3.2 Volatilisation

Volatilisation is the loss of herbicide vapour from plant or soil or water surfaces. A herbicide's vapour pressure represents its affinity for the air and is quantified by Henry's law constant (H). Henry's law for most herbicides varies between 10^{5} and 10^{-9} Pa/m^{3} mol K (Vighi and DiGuardo 1995). Henry's law constant values of greater than 10 signifies very high air affinity while a value less than 10^{-4} signifies very low air affinity.

The properties of the chemical together with the prevailing weather conditions determine the extent of volatilisation. Soil-incorporated herbicides have lower volatilisation losses than surface-applied ones (Taylor and Spencer 1990). The extent of volatilisation loss is also affected by soil sorption.

9.3.3 Soil degradation

Degradation occurs by chemical and biological (mineralisation) processes. Herbicide properties, soil type and environmental conditions influence both microbial activity and its rate of degradation. Herbicide use can also enhance the rate of degradation (Felsot and Shelton 1993). This is because frequent use of some herbicides may result in a build-up of a select group of micro-organisms in the soil, capable of degrading these herbicides.

Farenhorst (unpublished data) has shown that trifluralin mineralisation in soil decreases with increasing amounts of wheat residues in soil (Figure 28). In the presence of wheat residue, increased persistence of trifluralin is due to the soil micro-organisms utilising wheat residues as a food source while trifluralin is retained by the soil carbon.

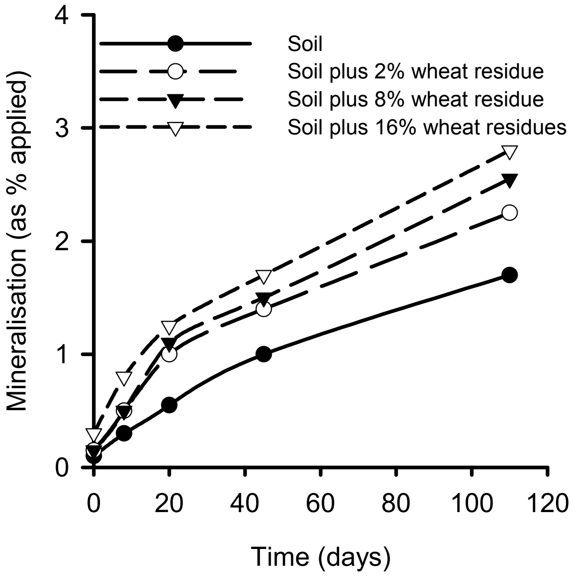

Figure 28 **Trifluralin mineralisation measured at three levels of wheat stubble in a silty loam soil (Farenhorst, unpublished data)**

9.4 Management impacts

Stubble is thought to reduce trifluralin efficiency by interception and sorption. The high ability of the soil carbon to sorb trifluralin has been interpreted to mean stubble retention will result in reduced herbicide efficiency. However, Bateman and Walker (1985) have shown maize stubble of up to 3.0 t/ha had no effect on the effectiveness of trifluralin.

Crabtree (1999) conducted an experiment at a site where a group A herbicide failed to control ryegrass in 1997. The experiment consisted of an application of a combination of trifluralin and Logran® applied immediately before seeding to treatments where wheat stubble was either burnt or retained before seeding, and the site either harrowed or not harrowed after seeding. These treatments resulted in a wide range of ryegrass plant density which most reduced wheat grain yield (Figure 29). Highest ryegrass densities ranging between 47 and 276 plants/m^2 were observed for the retained stubble plus harrow treatment compared to densities ranging between 4 and 27 plants/m^2 for the stubble burnt plus harrow treatment.

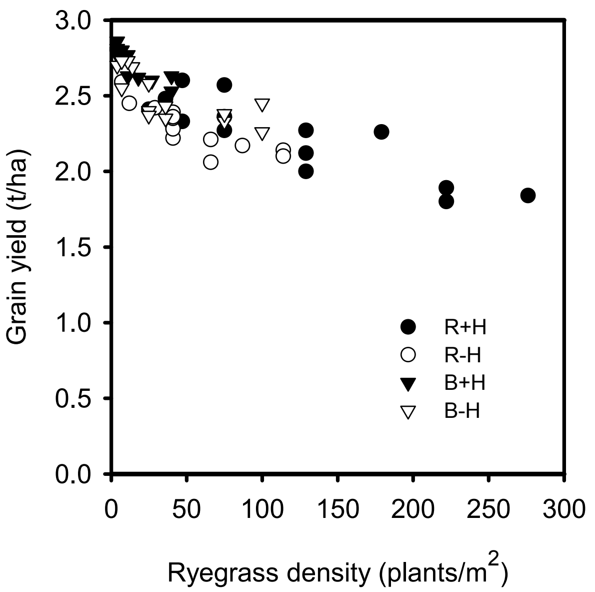

Figure 29 **Wheat grain yield (t/ha) response to ryegrass plant density (plant/m2) obtained for various stubble (R retained, B burnt) and harrow (+ plus harrow – minus harrow) treatments**

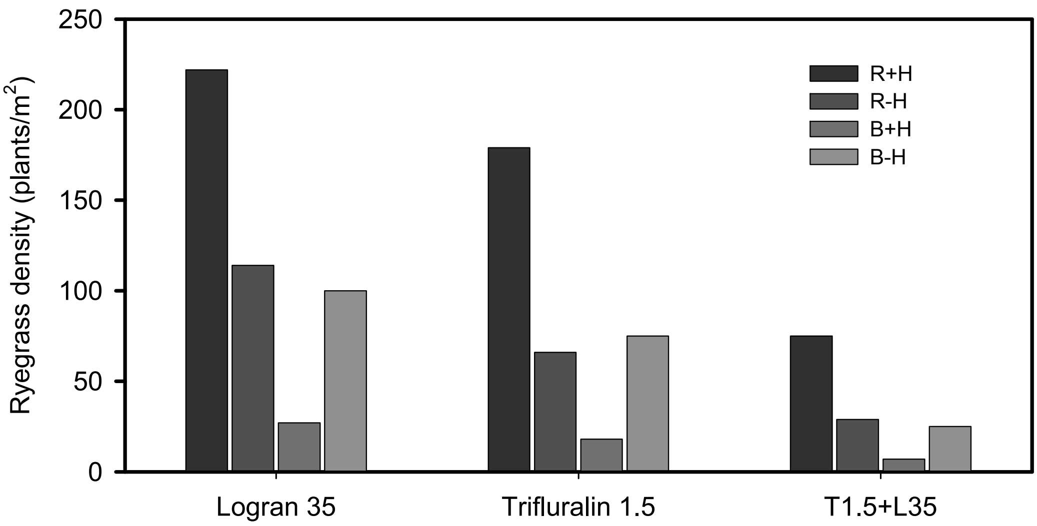

Figure 30 **Effectiveness of Logran® applied at 35 g/ha (L35) and trifluralin applied at 1.5 L/ha (T1.5) to control ryegrass with herbicide applied separately or together in stubble (retained or burnt) and tillage treatments (plus or minus harrows)**

Trifluralin and Logran® effectiveness were reduced when stubble was retained and harrows used (Figure 30). This effect could be due to higher weed germination in the harrow treatments, the retention of herbicide on stubble and the unevenness of incorporation due to the presence of stubble. It is interesting to note that the effectiveness of each herbicide was increased when both were used together. This increased effectiveness may be related to the higher herbicide input, a rate effect, or the different properties of the herbicides. However, the strategy of combining herbicides would not be recommended because it has the potential to increase the rate of development of herbicide resistance. In fact where herbicide resistance has developed, Newman and Adam (2004) observed no improvement in ryegrass control when either Diuron or Logran® was mixed with trifluralin.

Aslan and Turkman (2005) examined the potential of wheat straw to remove herbicides trifluralin, fenitrothion and endosulfan from drinking water. It was observed that about 2 per cent of trifluralin, 7 per cent of fenitrothion and 21 per cent of endosulfan were removed from solution by sorption onto the wheat straw. This compares to 96 per cent of trifluralin, 87 per cent fenitrothion and 68 per cent endosulfan removed by microbial decay. In contrast to wheat straw, activated carbon was observed to have a very high herbicide sorption capacity.

The main reason for reduced herbicide efficacy when burning stubbles is the sorption of herbicide by the ash. By incorporating the ash into the soil the adverse effect of stubble burning on herbicide efficacy can be reduced. More work is needed on the efficacy of soil-active herbicides under both stubble retention and burnt situations using higher rates of herbicides and water and different spray nozzles. In retained stubble, there is also a problem with effective incorporation of volatile soil-applied herbicides like trifluralin. High water application rates improve the effectiveness of both contact-applied and soil-applied herbicides through stubble.

10. Other factors

10.1 Disease

There are two key issues when looking at stubble management and the impact of disease on a crop. First, understanding the life cycle of the disease is paramount when looking at control options through stubble management. Second, the numbers of spores generated by fruiting bodies is enormous. Hence, the reduction in the level of inoculums in the stubble diminishes the chance of disease outbreak. Retaining stubble can increase spore loads of yellow spot, septoria and scald. Standing stubbles may create a micro-climate for certain diseases through increased humidity providing an environment for spore production.

10.1.1 Wheat

A major concern in the practice of stubble retention is an associated increase in certain plant pathogens that survive in surface-borne stubbles (Sutton and Vyn 1990). Two such pathogens of wheat giving most concern at present in the northern and central wheatbelt of WA are yellow spot (*Pyrenophora tritici-repentis*) and septoria nodorum blotch (*Phaeosphaeria nodorum*) (Murray and Brown 1987, Bhathal and Loughman 2001). These diseases often occur together in WA (Loughman 1994; Loughman et al. 1994).

Yellow spot grows saprophytically through the leaf and leaf sheath and into the stem as the infected plant senesces (Summerell and Burgess 1988). It produces abundant pseudothecia on affected wheat stubble and ascospores from these have been regarded as the main form of primary inoculum (Rees and Platz 1980). Wind-dispersed conidia are produced on infected leaves later in the season and serve as secondary inoculum (Hosford 1972).

Ascospore-producing perithecia of septoria nodorum blotch also survive the host-free period in infested stubble on the soil surface (von Wechmar 1966) and serve as primary inoculum. The amount of primary inoculum is an important determinant of the severity of disease over the crop season (Adee and Pfender 1989), even though both fungi produce splash or airborne secondary inoculum. Rees et al. (1982) showed a logarithmic relationship between grain yield loss from leaf disease and amount of infested stubble added to plots. It is therefore desirable to minimise the local primary inoculum by means of cultural and biological measures to ultimately reduce disease severity.

An important aspect of conservation farming is the management of diseases with rotations that include lupins. Reduction in leaf spot disease caused by yellow spot *P. tritici-repentis* with a one or two-year break in wheat production is reported in Canada (Sutton and Vyn 1990) and the United States (Bockus and Claassen 1992). Scientific information on the ability of retained wheat stubble to carry-over the disease in a rotation system under natural field conditions is needed to underpin disease management in stubble retention rotation systems. The extent to which retained wheat stubble contributes to the disease expression was investigated by Bhathal and Loughman (2001). The major objective of the study was to determine whether disease carry-over was a factor in the long-term viability of lupin–wheat rotations.

In WA, wheat is harvested from October to January, starting at the commencement of the dry summer period. Ascospores of both yellow spot and septoria nodorum blotch are usually first observed following rains that mark the commencement of the growing season in May. Under continuous wheat production, both fungi have readily survived on wheat straw for six months, until the parasitic phase of the disease cycle is reinitiated. The important role played by

wheat stubble in enabling septoria nodorum blotch and yellow spot to survive the inter-crop period is well known and confirmed from high disease levels initiated by six-month-old wheat stubble (Bhathal and Loughman 2001).

Bhathal and Loughman (2001) found that quantity and infectivity of stubble usually decline sufficiently during the rotation phase to prevent very early onset of yellow spot or septoria nodorum blotch. In the environment of WA, crop rotations as short as one year can contribute greatly to the control of yellow spot and septoria nodorum blotch by greatly reducing or eliminating early infection from local carry-over.

Crown rot of wheat (*Triticum aestivum* L.) is caused by *Fusarium graminearum* Schwabe Group 1. For this disease the influence of three stubble management practices—stubble retention, stubble incorporation and stubble burning—was examined for the incidence of crown rot, as well as plant development and grain yield (Summerell et al. 1989). Crown rot was highest in the stubble retention plots (59–81 per cent incidence), whereas stubble burning decreased disease incidence (16–47 per cent). Stubble incorporation was ineffective in reducing disease levels. Burning reduces the level of crown rot fungus which survives as mycelium in stubble and colonises the lower 3–4 internodes during its parasitic phase (Burgess et al. 1981). Grain yield did not differ significantly between treatments, but early season plant dry weight was reduced in the retained stubble plots.

Turley et al. (2003) examined the impact of stubble retention on the presence of take-all (*G. graminis* var. *tritici*) infection of roots. In general, take-all was observed to be low and not to be a limiting factor on grain yield in any season. In the years when take-all occurred, the level of infection was not significantly affected by straw disposal treatment at one site. But at a second site there was a suggestion that higher plant infection with chop/tine (57 per cent plants infected) compared with chop/plough and burn/tine (27–33 per cent infected) may have contributed to a yield reduction that year. At a third site take-all infection levels were generally low and the proportion of infected plants was unaffected by treatment. The exception was in one year where infection levels were higher where straw was shallowly incorporated (27 per cent plants infected) rather than burnt (15 per cent plants infected).

Recent work by Matthew McCallum (pers. comm.) has highlighted the benefits of tramline farming in term of disease management (see Table 23). Less soil-borne disease on the inter-row is the major contributing factor to this difference (Photograph 6). Inter-row sowing increased crop yield by 0.21–0.32 t/ha. However, in the absence of root disease an increased yield may be associated with another factor, as occurred at Hart and Buckleboo in 2005 (Table 23).

(a)  (b) 

Photograph 6 **(a) Take-all and (b) CNN infected wheat (left) from wheat sown on the previous season row compared to reduced disease levels (right) obtained from inter-row sown wheat**

Table 23 **Wheat-on-wheat yields in the inter-row sowing experiment 2004 and 2005**

Site	Sowing row	Grain yield (t/ha)	% increase	Disease effect
Sandilands SA 2004	Inter row	4.11	5.60	Take-all
	In row	3.88		
	LSD	0.21		
Tamworth NSW 2004	Inter row	2.51	8.37	Crown rot
	In row	2.30		
	LSD	na		
Sandilands SA 2005	Inter row	3.74	8.56	CCN and take-all
	In row	3.42		
	LSD	0.31		
Hart SA 2005	Inter row	2.99	7.36	None
	In row	2.77		
	LSD	0.13		
Buckleboo SA 2005	Inter row	2.82	1.06	None
	In row	2.79		
	LSD	ns		

In 2005 at Sandilands, South Australia there was a significant interaction between sowing row and stubble management for yield and protein (Table 24). Standing inter-row sowing gave the highest grain yield of 3.74 t/ha with a protein content of 11.3 per cent compared to 0.98 t/ha less grain yield for the slashed in-row sowing treatment. Possible reasons include increased disease levels and soil inorganic nitrogen immobilisation. Also, slashed in-row sowing had higher screenings levels (4.5 per cent) than the other treatments (1.5–2.5 per cent).

Table 24 **Third year wheat yield and protein content (%) obtained at Sandilands, SA**

Stubble	Sowing row	Grain yield (t/ha)	Protein (%)
Standing	Inter row	3.74	11.3
	In-row	3.42	10.3
Burnt	Inter row	3.33	10.6
	In-row	3.28	10.7
Slashed	Inter row	3.42	10.1
	In-row	2.76	10.7
LSD		0.31	0.58

In the presence of soil-borne pathogens, inter-rowing sowing using knife points and no-till with row spacings of 22.5–30 cm can reduce the impact of these diseases on wheat yield.

Brennan and Jayasena (2005) have illustrated that potassium nutrition reduces disease severity (Figure 31). In potassium deficient plants, cell walls weaken resulting in the leaking of soluble nitrogen compounds and sugars from leaves onto leaf surfaces, promoting the development of foliar diseases. With adequate potassium supply, cell wall strength, cuticle thickness and the production of phenols, all important for disease resistance in plants, increases (Marschner 2003).

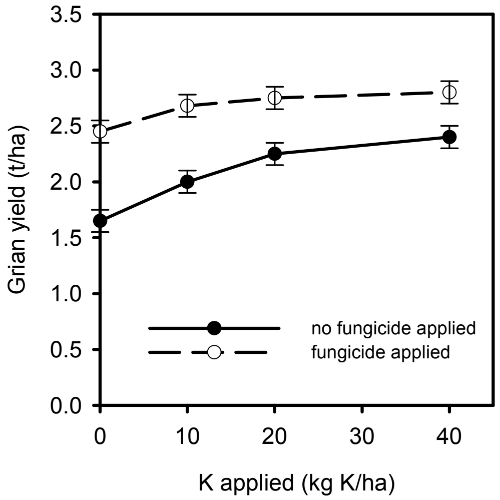

Figure 31 **Relationship between grain yield (t/ha) responses of barley to applications of potassium fertiliser (kg K/ha) when powdery mildew was the major disease present**

Note: (●) sulfate potassium source when no fungicide applied and (○) sulfate potassium source when fungicide was applied. Error bars are standard errors of the mean (n = 3).

10.1.2 Lupins

Retention of cereal stubbles is standard practice when growing lupins (*Lupins angustifolius* L.). Sweetingham et al. (1993) observed brown spot (*Pleiochaeta setosa*) incidence in lupins is reduced when cereal stubble is retained (Figure 32). Infection of lupins occurs due to rain splash of soil-borne spores of the fungus. The impact of the fungus is greatest when young seedlings are infected. Diseased leaves appear within a few days of the symptom expression and large quantities of pigmented thick-walled conidia are produced by the fungus on the leaf litter under the crop canopy. These conidia provide a source for further infection in the current season and accumulate in the surface layers of the soil to form a reservoir of inoculum affecting crops in subsequent seasons (Sweetingham 1990).

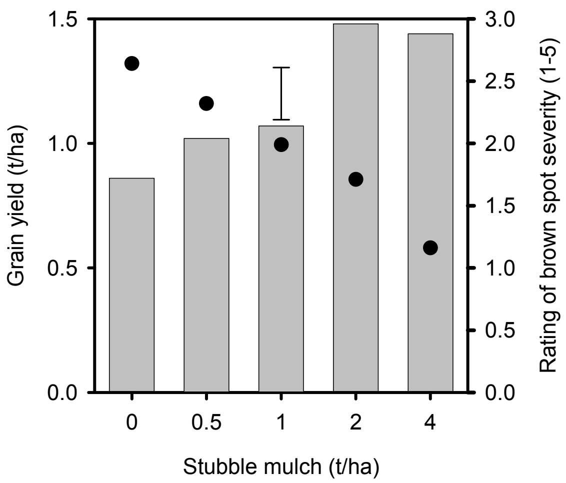

Figure 32 **Effect of cereal stubble mulch (t/ha) on brown spot severity (•) and lupin grain yield (t/ha)**

Brown spot control can be achieved by long rotations to reduce this soil-borne inoculum. But on sandplain soil types in Western Australia the most economic rotation is only 1–2 cereal crops between lupin crops (Rowland et al. 1986). Fungicide seed treatment can be used to

protect lupin crops from brown spot but the control is only partial (Loughman and Sweetingham 1991) and less effective than stubble retention (Sweetingham et al. 1993).

10.2 Allelopathy

Allelopathy occurs when phytotoxic allelochemicals are exuded by stubbles and plants so that the growth of other plants in the close vicinity, whether weeds or crop, is affected (Wu et al. 2000).

The application of crop allelopathy in weed suppression involves two crop growth stages: the vegetative stage and post harvest stage (Wu et al. 2000). At the vegetative growth stage, crop seedling allelopathy could be exploited to suppress weeds. At the post harvest stage, stubble allelopathy could be used for weed suppression, especially during the establishment period of the following crop. Wheat residue allelopathy on the growth of annual ryegrass has been found to vary with accessions (Wu et al. 1998).

10.2.1 Impact from stubbles

The deleterious effect of stubbles, usually of cereals, on the growth of following crops has been widely observed (Rice 1974; Lovett 1982; Cochran et al. 1977). Residues may also affect the growth of weeds which germinate in their vicinity (DeFrank and Putnam 1978). The effects of stubbles depend upon the release of phytotoxic chemicals which may be washed directly from the residues, or may result from microbial activity during decomposition (Lynch and Cannell 1980). The identity of the compounds has been discussed by Rice (1974) and many such chemicals may be active in allelopathy during the life of the plant.

Lovett and Jessop (1982) assert that with the increased use of techniques such as stubble retention and minimal cultivation, the incidence of phytotoxic effects seems likely to become more widespread, particularly where oilseeds and grain legumes are growing in rotation with cereals. They observed that residues of a range of crop plants affect germination, emergence, height of the coleoptile and length of the longest seminal root of wheat. Rape and some leguminous crops residues exerted the greatest phytotoxic effects. Phytotoxicity was increased when stubbles were incorporated into soil rather than being left on the surface. The phytotoxins did not kill the test species, but Lovett and Jessop (1982) argued that their effects would disadvantage such a species under field conditions and that instances of such effects are likely to increase as minimal tillage and stubble retention become more widely adopted.

10.2.2 Impact from crop growth

Allelopathy has been receiving world-wide attention for its potential in integrated weed management (Wu et al. 2000). Wu et al. (2000) observed that wheat seedling allelopathy had the potential to inhibit root growth of ryegrass by 10–91 per cent in a collection of 453 wheat accessions originating from 50 countries. Wheat seedling allelopathy also varied significantly with accessions from different countries. Wheat allelopathic activity was normally distributed within the collection, indicating the involvement of multiple genes conferring the allelopathic trait. Of the 453 wheat accessions screened, 2 distinct groups were identified. Condor-derivatives were more allelopathic than Pavon-derivatives, with an average inhibition of root growth of ryegrass by 76 per cent and 46 per cent respectively. Research was further extended to investigate the near isogenic lines derived from Hartog (Pavon-derivative) and Janz (Condor-derivative). Hartog and its back-crossed lines were less allelopathic than Janz and its back-crossed lines, inhibiting root length of ryegrass by 45 per cent and 81 per cent respectively. These results strongly indicate that wheat allelopathic activity might also be controlled by major genes, depending on the particular populations. The present study

demonstrates that there is a considerable genetic variation of allelopathic activity in wheat germplasm. It is possible to breed for cultivars with enhanced allelopathic activity for weed suppression.

10.3 Light interception

Bruce et al. (2005) observed that wheat stubble at levels of less than 4 t/ha has limited impact on canola grain yield. However, at levels greater than 5 t/ha, it reduced canola emergence by 25 per cent, plant establishment by 33 per cent and grain yield by 23 per cent. The lower grain level is associated with reduced plant density, delayed development, reduced leaf number and area during stem elongation and reduced vegetative biomass. The effect is similar to the impacts of delayed sowing (Hocking and Stapper 2001) and is caused by reduction in hypocotyls elongation, mainly due to reduced light penetration to the seedlings.

Bruce et al. (2006c) showed how sowing techniques that moved wheat stubble away from the zone directly above the seed into the inter-row can alleviate the adverse effect of surface-retained wheat stubble. Surface-retained wheat stubble resulted in slower rate of seedling emergence, reduced seedling density, reduced leaf area and longer hypocotyls (Photograph 7). Canola yield in systems where stubble was pushed onto the inter-row was generally similar to canola yields obtained from the bare ground treatment which was greater than the yields obtained for the stubble-spread treatment (Table 25).

Table 25 **The effect of wheat stubble retention on canola plant density and yield observed under various wheat stubble retention systems (Bruce et al. 2006c)**

Site	Measurement	Bare	Inter-row stubble	Spread stubble	SED
1	Density	45	35	22	4
2	Plants/m^2	27	17	13	ns
3		99	57	70	6
4		49	39	29	6
1	Yield (t/ha)	3.5	3.3	2.3	0.3
2		2.2	1.5	0.90	0.2
3		6.0	4.9	4.2	0.4
4		3.5	4.6	3.8	ns

The negative effect of retained wheat stubble is associated with changes in the microclimate at the soil–stubble interface that were reduced by pushing stubble off the seeding row. This resulted in higher photosynthetically active radiation and temperatures, and reduced hypocotyl elongation of the canola seedlings. These effects were largely physical and not biochemical, and are consistent with the observations of Bruce et al. (2006a, 2006b)

Photograph 7 **The effect of (a) bare, (b) stubble inter-row, and (c) stubble spread treatments on seedling growth at site 1**

The sowing techniques of using narrow points and aligned press wheels without trailing harrows in the direction of previous rows, generally result in the retention of wheat stubble in the inter-row. This technique is commonly used in WA and other parts of the world (Azooz and Arshad 1998), although in some cases results have been inconsistent (Janovicek et al. 1997) due to poor clearing of stubble from the row. Hence other stubble manipulation practices may be required such as cutting, grazing or increasing row spacing in order to achieve consistent results. Simple laboratory screens such as that used by Bruce et al. (2006a, 2006b) may identify canola genotypes more suitable to conservation cropping systems and more tolerant of retained wheat stubble.

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