Row spacing of winter crops in broad scale agriculture in southern Australia

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Foreword

This Graham Centre Monograph *Row spacing of winter crops in broad scale agriculture in southern Australia* reviews current knowledge on the impacts on yield of widening row spacing for crops including wheat, barley, canola and lupins in southern Australia. Widening of row spacing has accompanied the adoption of conservation cropping systems with no-till and stubble retention. Row space widening has allowed sowing machinery to operate in stubble with minimal blockages caused by the retained stubble.

Conservation agriculture claims to improve soil condition and water conservation, but unintended other consequences, such as herbicide resistance and disease, can impact on crop yield. These outcomes were discussed in the first Graham Centre Monograph *Stubble retention in cropping systems in Southern Australia: Benefits and challenges.*

Stubble retention has been widely adopted in the lower rainfall zones of the southern wheatbelt (<350 mm rainfall per annum), but uptake has been less in the medium to high rainfall zones and under irrigated crops due to heavier stubble loads and resulting blockages in sowing equipment. While the benefits of stubble retention are well known, the common practice in these environments is for stubble retained over summer to be burnt during late autumn, before sowing, to minimise problems at sowing. To avoid burning, some crops are grown at a wide row spacing (35+ cm compared with the standard 18 cm spacing) to allow greater quantities and lengths of crop residues to pass through the sowing machinery.

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Editors

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1. Summary

This monograph reviews the claimed advantages and disadvantages of wide rows and, in Australia, quantifies the effects of widening rows on yields in wheat, barley, canola and lupins. General conclusions have been drawn.

Farmers have adopted wider rows (>18 cm) to improve the passage of sowing machinery through stubble. The direct effect of wide rows on yield often has been either minimised or overlooked in adopting the practice while the other advantages of wide rows have been emphasised. Frequently identified advantages of wide rows, beyond stubble clearance, include reduced fuel consumption, with fewer ground-engaging components, and increased speed of the sowing operation. Other claims about the advantages of wide row spacing, including improved harvestability, seed size, grain quality and higher yield appear to be, in reality, limited and inconsistent.

Crops sown in wide rows are considered less competitive with weeds and at increased risk of seedling damage from close fertiliser placement. In addition, crops sown in wide rows have reduced plant populations compared with those sown in narrower rows, even when fertiliser and seed are placed separately.

Historically, square planting arrangements with cereals have higher yields compared with rectangular patterns. On this basis widening rows, and hence moving to a more rectangular pattern, could be predicted to reduce grain yield of cereals. Data from 89 experiments on wheat, available across Australia, were examined for preparation of this monograph. The yield change (kilograms per hectare per centimetre of row space widening) was related to estimated yield at 18 cm row spacing (a common spacing in earlier Australian agriculture). The rate of yield loss (kg/ha/cm) with row widening increased as yield in 18 cm rows increased, although there was considerable variability between experiments.

Generally, at yields below 700 kg/ha, widening row spacing beyond 18 cm increased estimated grain yield. For example, at yields of 500 kg/ha, doubling the row space to 36 cm increased yield to 520 kg/ha. However, at yields of 2000 kg/ha, widening rows

to 36 cm reduced yield to 1860 kg/ha, and at 4000 kg/ha yield was reduced to 3640 kg/ha with 36 cm row spacing.

Although only 18 experiments were identified for barley, the rate of change of yield with changes in row spacing was similar to wheat. This suggests wheat and barley are similar in their reaction to row space changes. At yields of <1100 kg/ha at 18 cm row spacing, widening rows increased barley yield.

Canola yield declined as row spacing increased, and the rate of decline was greater as yield with 18 cm rows increased in Western Australia (14 experiments), and central and southern NSW (13 experiments). The rate of decline was not significantly different between the two states, and was not different from the relationship obtained for wheat.

Data were assembled on lupins from WA (29 experiments) and NSW (10 experiments). In WA lupin grain yield related to row spacing was not always linear. A two-phase linear approach, limiting the range of data to more closely approximate linearity, addressed this issue. In the row spacing range of 18-30 cm minimum, and 42-60 cm maximum, lupin yield increased more frequently with increased row spacing in WA. This result contrasted with that of wheat and canola in the same State. Data from NSW indicated lupin yields generally decreased as row spacing widened, but there was insufficient data to fit a linear function. In WA when rows were widened further, from beyond the range 42-50 cm minimum to 84-100 cm maximum, yield reduced with wider row spacings.

A number of studies have examined changes in agronomic practices (for example, weed control, sowing time, cultivar and fertiliser management) and their effect on yield under wider rows. It was implicit from the present study that any agronomic practice that lowered grain yield in 18 cm rows was likely to also lower the rate of yield loss (kg/ha/cm) as row spacing increased. The agronomic practices that commonly produced the highest yield at 18 cm rows also produced the highest yield at 36 cm rows. The suggestion is that yield at 18 cm row spacing has a dominant influence on yield at wider row spacing, and differences in the rate of reduction of yield between practices are smaller in their effect on yield at wide rows. Retention of stubble compared with removal, did not directly affect the loss of yield with increased row spacing. Any effects on yield loss with wider rows were indirect and were through changes in grain yield at 18 cm induced by stubble management.

The most appropriate action to maximise grain yield at wide rows seemed to be sound agronomic practice and cultivar selection. This approach generally produced the highest yield irrespective of row spacing. 'Paired or ribbon row' sowing appeared to offer some scope in mitigating the loss of grain yield as row space increased.

From the point of view of adopting conservation farming techniques, increasing row spacing is an 'enabling' change, which makes sowing through stubble achievable. The benefits in stubble handling are greatest with high stubble loads. High stubble loads are more frequent in higher rainfall areas with higher grain yields; the conditions where reductions in grain yields from wide rows are likely to be greatest. Long term data from Wagga Wagga (high rainfall wheatbelt NSW: average yield 3440 kg/ha), Condobolin (low rainfall NSW: 1840 kg/ha) and Merredin (low rainfall WA: 2230 kg/ha) were used to estimate the losses in grain yield from wide row spacings.

The loss of yield at Wagga Wagga for row spacings of 30 cm and 36 cm would be 200 kg/ha and 300 kg/ha. The loss of yield resulted from row widening, but needs to be compared with any cost savings or advantages associated with wider rows.

Results from this review suggest farmers regularly managing high stubble loads at sowing avoid increasing row spacings where possible. If there are no other palatable options to manage stubble at sowing, farmers are advised to keep row spacings as narrow as possible while still permitting unimpeded sowing through stubble.

2. Introduction

Row spacing in broadacre cropping became an issue when widening of rows was recommended to enable conservation sowing machinery to operate through retained stubble (Anon undated). Conservation farming, including stubble retention, was widely adopted in Australia during the decade after 1995 (Llewellyn and D'Emden 2009). Until then, traditional row spacing had been about 18 cm (7 inches) (Kleemann and Gill 2010b), but this increased up to 36 cm (14 inches) (referred to as wide rows in this monograph), and more recently to beyond 36 cm, to 60 cm or 70 cm (very wide rows) (Blackwell *et al.* 2006; Jones and O'Halloran 2006; Buck and Keys 2008).

Wider rows appear to have been recommended, and adopted by farmers, in pursuit of a no-till farming system with retained stubble. This may result from extension literature where possible yield loss from wide row spacing is either not mentioned (for example Speirs *et al.* 2007), or possible losses have been noted and minimised. Anon (undated) has indicated that '..cereal yields are *slightly reduced* by wide row sowing (30 cm)…'. In WA, Leonard (1993) suggested that '…wide row spacing of wheat (*Triticum aestivum* L.) reduces yields by *only a small amount...* wheat grain yield is reduced by 4 per cent as row spacing is increased from 18 cm to 36 cm'.

These general statements may have resulted from research that suggested wide row spacing could increase, or not affect, yield in some low yielding situations. Hill (1988), working in low rainfall southern NSW, concluded that row spacing within the range of 17.5 cm to 30 cm had 'little effect on lower yielding dryland crops'. Fettell and Bamforth (1986), in low rainfall central NSW, indicated yield depressions in wheat at wide row spacings (36 cm) were evident at high yield levels (about 3000 kg/ha), but not under lower yields (about 1000 kg/ha), but did not indicate a yield threshold where yield depression may be expected. Yield depression due to very wide rows has been suggested at yields above 1000 kg/ha in the Victorian Mallee (Jones and O'Halloran 2006) or in wide rows above 1500 kg/ha in South Australia (Smith *et al.* 1995).

This monograph examines the claims of advantages and disadvantages of wide rows, including effects on weed competition and control, harvestability, seed size and grain quality. The authors have sought to capture as much data as possible in Australia in order to quantify the effects of wide rows on yield in wheat, barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.) and narrow-leaf lupins (*Lupinus angustifolius* L.). General conclusions have been drawn based on the data.

2.1 Current farmer practice

Current farmer practice is to widen row spacing to accommodate stubble retention associated with conservation farming. This was demonstrated with 32 farmers associated with conservation farming in southern NSW and 19 from central NSW. These results are presented below (Figure 1). In southern NSW 15 farmers were associated with conservation farming demonstrations (Holding 2010) and 17 were interviewed at a conservation field day during March 2011 (H Burns pers comm.). These interviewees had more than five years experience with stubble retention. The row spacing used by 19 of the 20 farmers using conservation farming in central NSW was established. The central NSW group was reported as case studies in conservation farming (Anon 2008).

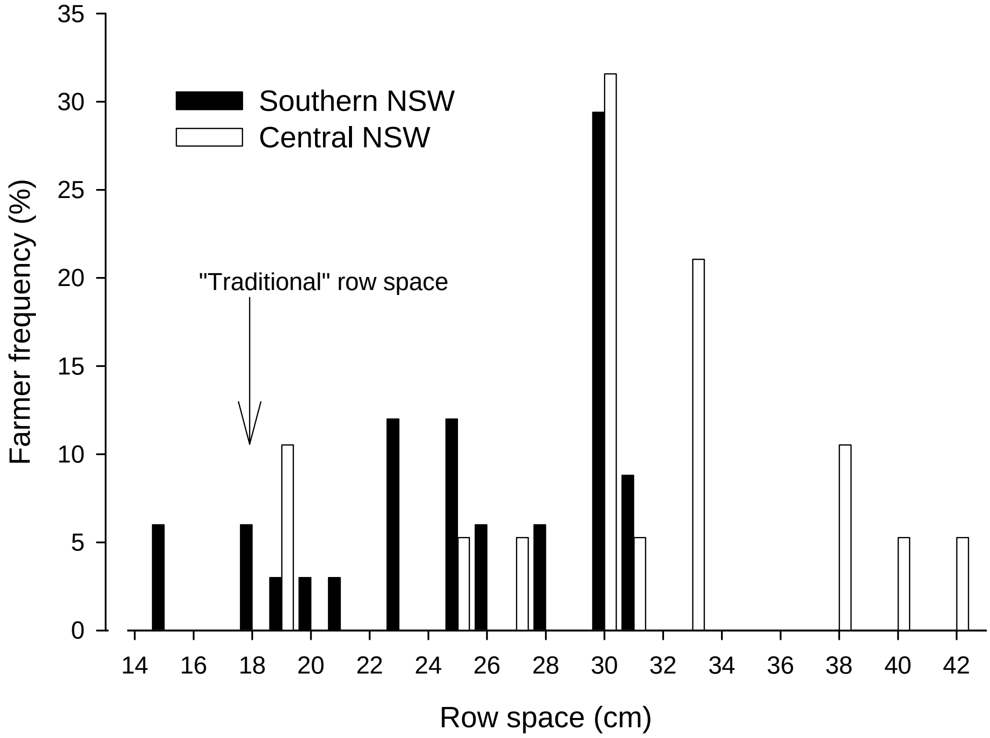

Figure 1 The row spacing used by 32 farmers experienced with stubble retention systems in southern NSW, and 19 farmers in central NSW.

The most frequently used row spacings were 23-26 cm and 30-33 cm (Figure 1). Some farmers in central NSW used very wide row spacing (> 36 cm), which was not apparent in southern NSW.

There appeared to be a progression in the widening of rows in some instances. One case study in Galong, southern NSW (Holding 2010) mentioned widening rows from 22 cm to 30 cm. Survey results for southern NSW indicated farmers moving from 17.5 cm to 25 cm, and from 22.5 cm to 30 cm. In central NSW some farmers reported increasing row spacings since 2008; from 33 cm to 37 cm, and from 30 cm to 41 cm.

Farmers using 30-33 cm spacings were most frequently doing so to enable inter-row sowing of subsequent crops (i.e. to sow a new crop between the standing rows of stubble from the previous crop). Widening row spacing beyond 33 cm seemed to occur when farmers perceived no yield penalty with further row space widening.

In southern NSW two farmers were using 15 cm spacing and two were using 18 cm spacing. One gave the reason for using 18 cm row space as the ’need‘ for pasture sowing; presumably rows of lucerne (*Medicago sativa* L.) were perceived as ’too wide‘ from wide row sowing. In dryland grazing situations pasture productivity was unlikely be reduced by wide rows, as density of lucerne can be low (4-6 plants/m^2) in productive pastures (Wolfe and Southwood 1980; Hall *et al.* 1985). However, groundcover may be reduced. The two farmers using 15 cm row spacing indicated they intended to replace current machinery with wide row machinery in the future.

3. Potential advantages and disadvantages of wide row spacing

There were numerous assertions as to the advantages and disadvantages of widening row spacing (Table 1). This monograph reviews these claims. Two items in Table 1 appear as both advantages and disadvantages; these relate to harvestability and grain yield. The effects and implications of wide row spacing on yield are presented in section 4, ‘Row spacing and yield’.

Table 1 Claimed advantages and disadvantages of using wide row spacing in cropping (after Martin et al. 2009).

Advantages of wide rows	Disadvantages of wide rows
1. Increased stubble handling ability of sowing equipment	1. Grain yield reduced in many situations
2. Lower cost of machinery operations	2. Fertiliser toxicity
3. Options for inter-row weed control	3. Reduced plant populations
4. Improved harvestability	4. Reduced competitiveness with weeds
5. Improved grain quality	5. Reduced harvestability in some situations
6. Compatibility within farming systems	
7. Improved grain yield when water saved for grain fill	

3.1 Stubble handling

Stubble can be managed at harvest (low cutting height and even trash spreading) and after harvest where options include grazing with livestock, slashing, mulching or harrowing and strategic burning. Remaining stubble at sowing can be a physical barrier to the sowing operation. Widening row spacing is one of a suite of machinery design features or modifications that avoid blockages while sowing through stubble. Modifications include those to the tine itself; increasing the height of the tine, and changing the shape of the tine from rectangular to more circular to shed stubble more readily. Tine arrangement on the implement can be changed by increasing the length between rows of tines, and increasing the spacing of tines within the row (Mead and Qaisrani 2003). Disc seeders are less likely to block in stubble than tined implements. Coulters can cut stubble, though not always successfully. ‘Fingered’ wheels can sweep stubble from in front of the sowing tine or disc (Green 1997), or rubber-fingered wheels can be used to ’walk down‘ the stubble preventing stubble from building up on the soil opener (Siemens *et al.* 2004).

Inter-row sowing is primarily an innovation to improve stubble handling by sowing machinery. With wide rows (say 30 cm) a new crop can be sown in the inter-row space of the previous crop (between the rows of standing stubble). In this situation the stubble rows pass through the sowing machinery undisturbed by the sowing tines. A high standing frame on the sowing machine and/or low cut stubble reduces any contact between sowing machinery and stubble.

3.2 Machinery cost and operation

There has not been a premium in maintaining an 18 cm row space, as other advantages accrue from having fewer sowing tines or discs. These include less power and fuel consumption with fewer ground-engaging components, and fewer of these components to wear and maintain. These advantages can be captured by using a smaller tractor, with less horsepower, to carry out sowing operations, so reducing capital expenditure and fuel. Alternatively, the speed of travel in the sowing operation could be increased using the same machinery, or wider sowing machinery could be used behind the same tractor.

‘Soil throw’ can be a challenge with sowing machinery operated at speed; soil can be displaced from the sowing row giving poor seed cover in that row and/or soil can be thrown to cover neighbouring rows, resulting in these rows being too deeply sown

(Desbiolles and Kleemann 2003). This excessive soil movement can become a further problem if soil-incorporated herbicides have been applied.

3.3 Wide row sowing and weeds

General considerations

Numerous Australian field studies emphasise the need to control weeds when sowing crops in wide rows, as these crops are considered less competitive with weeds (for example Hill 1988; Smith *et al.* 1995; Felton *et al.* 2004; Peltzer *et al.* 2009). The control of weeds in wide row spacing is easier to manage when effective herbicides are available. The studies of crop sequencing and crop/weed competition are important as the efficacy of herbicide declines through development of resistance in weeds. Peltzer *et al*. (2009) reviewed weed management in cropping systems with wide row spacing. They concluded: ‘Crop competition is reduced with wider rows, so weed management relies more on herbicides and tillage’. Whereas Lemerle *et al.* (2013) found that crop sowing rate had a greater impact than row width on competitive ability. Herbicide reliance brings risks such as resistance, species shifts and or changes in species dominance, crop damage and increased costs.

A major agronomic issue in the examination of crop row spacing has been the differential impact of weeds on grain yield at different spacings. Another important issue was whether, at wide crop row spacings, weeds can set larger amounts of seed. If this is the case, then subsequent crops (presumably also sown at wide row spacings) will experience a higher initial weed burden.

Most experiments have examined the first year of this sequence only and either described initial weed burden, or sown a population of weeds. Only one study in Australia has examined sustained wide row sowing (Riethmuller 2004b). Despite weed control with herbicides and crop sequencing Riethmuller (2005) found that, in the 18th year of this row spacing study, increasing row spacing in wheat from 18 cm to 36 cm increased the number of annual ryegrass seeds (*Lolium rigidum* Gaudin) captured in the harvested grain by an average of 292%. In a drier season ryegrass seed numbers captured in the harvested grain increased by 613% as row spacing of barley was increased from 18 cm to 36 cm (Riethmuller *et al.* 2008a). Riethmuller (2006) reported a similar increase (298%) in ryegrass seed numbers captured in the harvested grain when row spacing in semi-leafless field peas (*Pisum sativum* L.) was widened from 18 cm to 36 cm.

Weed competition and weed control

Most of the studies of competition of crops with weeds have used biomass of weeds as a measure of their competitiveness. Weed biomass may also give an estimate of the potential weed seed set and seedbank additions. Some reports have measured weed seed set directly, weed tiller number and/or weed number as estimates of weed competition with crops. It seemed there was no single method that fitted all situations.

Changing row spacing and sowing rate of the crop have been shown to influence competition between crop plants and competition of crop plants with weeds. Fischer and Miles (1973), in a theoretical study, showed weeds were most effectively suppressed by sowing the crop in an equilateral triangular lattice, but a square lattice was nearly as effective (Figure 2). They also showed the efficacy of a rectangular lattice declines rapidly as the rectangularity increases (rectangularity = length of long side of a rectangle/short side). If sowing rate is maintained, rectangularity in crop sowing increases as row space increases; plants are closer together within the row and further apart between the rows. Thus increasing row space is likely to result in decreased competitive ability with weeds. Kemp *et al*. (1983) from a series of five experiments across a range of plant densities and rectangularities, suggested that the time course of exploitation of space was important when determining crop yields. Available space was exploited more rapidly from square compared with rectangular sowing arrangements. This more rapid exploitation of the space increased the suppressive effect of the crop on the weeds.

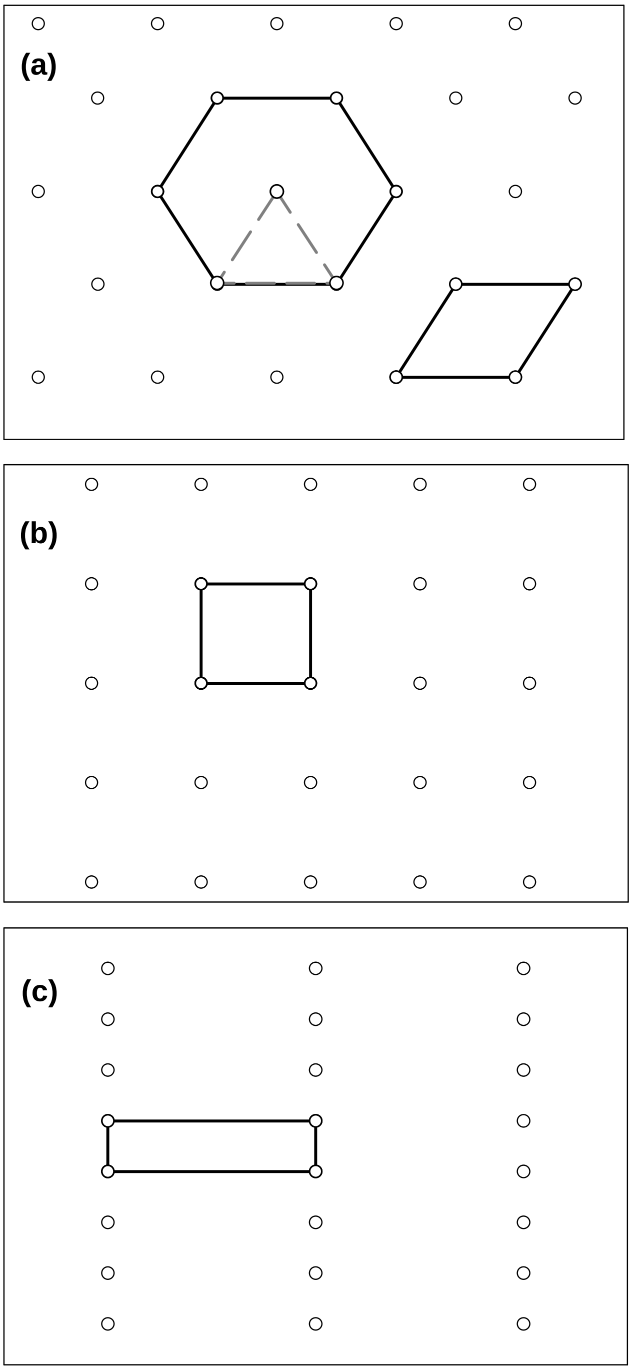

Figure 2 Spatial patterns of plant arrangement (a) equidistant or equilateral triangular lattice (Fischer and Miles 1973), or hexagonal (Holliday 1963) or rhomboidal pattern (Auld et al. 1983), (b) square pattern; rectangularity = 1 and (c) rectangular pattern, accentuated in wide row spacing (rectangularity >1).

The effect of crop density on competition with weeds is well documented. Increased crop density has been reported to reduce the effects of weed competition in wheat

(Lemerle *et al.* 2004; Blackshaw *et al.* 2005; Lemerle *et al.* 2013), chickpeas (*Cicer arietinum* L.) (Whish *et al.* 2002), field peas (Lemerle *et al.* 2006), canola (Daugovish *et al.* 2003; Blackshaw *et al.* 2005), barley (O'Donovan *et al.* 2000; Paynter and Hills 2007) and lupins (French *et al.* 2008).

The greater suppression of weeds by crops in narrow rows compared with wider rows has not always been demonstrated in reviewed studies, and it varies between crops, row spacings and environments. A wide range of row spaces has been compared, ranging from 9 cm to 100 cm. Many of the studies compared two row spacings, designated as ‘narrow’ and ‘wide’. Presumably this was because changing the row spacing of sowing equipment was sometimes difficult; however, blocking every second row achieves double the row spacing. Some comparisons have used 36 cm and 64 cm, while others have used 18 cm and 36 cm. It remains unclear whether it was appropriate to extrapolate the broad categorisation of ‘narrow’ and ‘wide’ to all situations.

Borger *et al.* (2010) compared barley, wheat, canola, field peas and lupins in three experiments at 18 cm and 36 cm row spacings, and one experiment at 23 cm and 60 cm row spacings. Row orientation (north-south versus east-west) and a range of sowing rates were also evaluated. East-west orientation, compared with north-south orientation, reduced weed biomass by 51% and 37% in wheat and barley respectively. However, the effects on weed biomass of east-west orientation in peas, canola and lupins were variable and inconsistent. Weed biomass, averaged across all experiments and crops, was slightly lower at narrow spacings of 18 cm or 23 cm (93 g/m^2) compared with wide spacings of 36 cm or 60 cm (107 g/m^2). The cereal crops intercepted more light when sown in the east-west than in the north-south orientation, which shaded the weeds, which were of shorter stature.

Champion *et al*. (1998) reported no effect on weed dry matter in cereal crops between narrow and wide rows in the United Kingdom. However, the row spacings tested were both very narrow at 9 cm and 15 cm. Lemerle *et al*. (2002) using row spacings of 23 cm and 46 cm with wheat found no difference in weed biomass due to row spacing. However, others have found narrow rows to effectively reduce weed biomass in wheat (Drews *et al.* 2009; Borger *et al.* 2010).

With lupins in WA, French *et al*. (2008) reported '...no consistent evidence that growing lupins in wide rows leads to increased weed growth and seed production…'. However, in pulse crops narrow compared with wide rows significantly reduced weed dry matter during some seasons. This effect has been reported in lupins and peas (Borger *et al.* 2010), soybeans (*Glycine max* (L.) Merr.) (Hock *et al.* 2006), faba beans (*Vicia faba* L.) and chickpeas (Felton *et al.* 2004). As with lupins, chickpeas appeared to maintain grain yield when row space was widened to 64 cm or 75 cm (Felton *et al.* 1996; Felton *et al.* 2004), but chickpeas competed poorly with weeds at any sowing rate or row spacing (Felton *et al.* 2004). Weed control within chickpeas was critical to achieve maximum yields. However, Whish *et al.* (2002) found consistent grain yield losses in weed free situations, when rows were widened from 32 cm to 64 cm, and claimed there was no greater yield loss in the presence of weeds.

Cereals seem to be able to suppress weeds more effectively when sown in narrower rows at higher sowing rates compared with wider rows and lower sowing rates (for example, Drews *et al.* 2009; Borger *et al.* 2010). However, the effect has been inconsistent (Lemerle *et al.* 2002) and there have been some reported differences between cereal species in their competitive ability (Lemerle *et al.* 1995). Increased sowing rates of canola also seem to increase suppression of weeds. However, suppression of weeds in response to narrower row spacings is not always successful (Lemerle *et al.* 2002).

Weeds, row spacing and grain yield

Solie *et al.* (1991) carried out 16 experiments in Oklahoma, United States of America, on the interaction of the weed cheat grass (*Bromus tectorum* L.) on wheat at three row spacings (7.5 cm, 15 cm and 23 cm). Solie *et al.* found that yield losses, due to cheat, were similar at all row spacings. However, they recommended very narrow row spacings (6.6 cm) due to estimated maximum yield at this spacing. Fettell and Bamforth (1986) indicated that weeds (sown annual ryegrass) depressed grain yield of wheat at all row spacings (range 15 cm to 35 cm) tested at Condobolin NSW, and at wide row spacings annual ryegrass did not appear to impact disproportionately on grain yield of wheat.

Felton *et al*. (2004) identified differences in crop species’ response to weed populations at row spacings of 32 cm and 64 cm. The weed sown was triticale (× *Triticosecale*), as a surrogate for wild oats (*Avena fatua* L.). The percentage grain yield losses of wheat in response to increased weed populations were unaffected by row spacing in three seasons, while those of canola, chickpea and faba beans varied. Canola and chickpeas lost a greater percentage of yield to weed competition at the wide row space (64 cm) than at the narrower row space (32 cm). The impact of weeds on faba bean yield was smaller, but tended to be slightly greater at wider rows. The effect of wide row spacings on yield is discussed in detail in section 4 'Row spacing and yield'.

Inter-row weed control

Sowing on wide row spacings has been shown to enable weeds in the inter-row space to be controlled by mechanical means or by foliar or soil applied herbicides using shielded sprayers. This practice has been common in summer cropping with maize (*Zea mays* L.), sorghum (*Sorghum bicolour* (L.) Moench) etc, but with winter crops in Australia, weed control in the inter-row has been pursued only in lupins in WA (Riethmuller *et al.* 2007).

Sowing lupins in wide rows is recommended in the northern and parts of the central wheatbelt of WA (Harries and French 2007), where it is claimed wide rows do not carry a grain yield penalty (see section 4.9 'Row spacing in narrow-leaf lupins'). The practice aims, in part, to control annual ryegrass, which has become resistant to some selective herbicides. The inter-row space can be sprayed with knockdown herbicides, such as glyphosate (Riethmuller *et al.* 2007) or paraquat and diquat (Hashem *et al.* 2008). Alternatively the inter-row space can be cultivated (Harries 2006; Peltzer 2006). In lupins in WA, simazine is commonly applied as a band on the sown row (intra-row space). A general claim that non-selective herbicides are less expensive than selective herbicides has lead to the combination of non-selective herbicides in the inter-row with a band of selective herbicide in the intra-row being promoted as more cost effective than the broad use of selective herbicides (Blackwell and Collins 2002; Crabtree *et al.* 2002).

While Riethmuller *et al.* (2007) found glyphosate was the most effective treatment of the inter-row space they warned of the possibility that the use of glyphosate as a pre-sowing knockdown spray, and as an inter-row herbicide, could increase the risk of developing glyphosate resistance in annual ryegrass. Evans *et al.* (2009) supported this possibility with modelling studies and suggested that using glyphosate as an inter-row spray in lupins in a wheat/lupin rotation was likely to be more conducive to developing glyphosate resistance in annual ryegrass than only using glyphosate as a pre-sowing knockdown spray. Maximum risk occurs when applying both uses concurrently.

Cultivating and spraying non-selective herbicides in the inter-row space requires row spacings of 50 cm or more (Harries and French 2007). It is only in lupins in parts of WA that such wide row spacings are used in winter cropping operations, although there have been claims of adoption in Victoria and NSW (Crabtree *et al.* 2002). In an inter-row cropping system, the inter-row space carries the stubble of the previous crop and this can interfere with spraying and cultivating operations. Riethmuller *et al.* (2007) noted that stubble caused blockages when cultivating the inter-row space.

Higher ground speeds at sowing can be accompanied by 'soil throw'. The problem of excessive soil throw has been outlined earlier in the monograph. Wider row spacings have been shown to partially ameliorate this problem, as the neighbouring rows are further from the sowing tine and less likely to be covered by soil throw. However, in practice ground speeds at sowing are often higher with wider row spacing increasing soil throw. Soil from the sowing row is thrown to the inter-row space reducing the effective rate of application near the seed and increasing effective application rates in the inter-row space. The combination of wide row sowing and higher ground speed at sowing has been used to increase the application rates of pre-sowing soil-applied herbicides (Haskins 2012). For example, the label rates of trifluralin are higher for no-till where incorporation is by sowing, than for incorporation by cultivation (Anon 2009).

3.4 Improved harvestability

Wider row spacings can often make crops taller, due to higher plant density in the row and inter-plant competition for light. Lupins can be short in late sown crops or dry seasons, which can make them difficult to harvest. Harries and French (2007) observed this short stature in lupins (Figure 3). The height to the lowest pod increased from 37 cm to >42 cm at very wide rows (100 cm). Riethmuller *et al.* (2008a) noted that for barley in a dry season, at 18 cm rows, the barley was 21.7 cm tall, and at 36 cm rows it was 23.3 cm in height.

Semi-leafless field peas are upright with relatively short tendrils that connect plants to each other. When row space was widened from 9 cm and 18 cm to 27cm and 36 cm peas tended to lodge (Riethmuller 2006). While lodging did not appear to present harvesting problems in this instance, widening rows from 18 cm to 36 cm lowered yield by 14%.

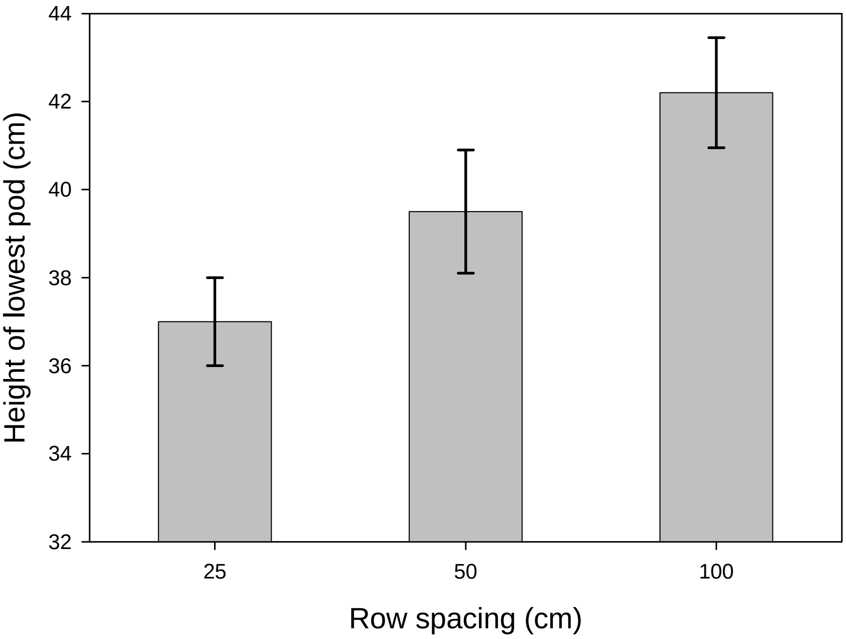

Figure 3 The height of the lowest pod of lupins increased with widening row spacing at Mullewa, WA in 2004 (from Harries and French 2007), reprinted with permission[1].

Wider row spacing has been associated with reduced lodging in irrigated wheat in southern NSW (Stapper and Fischer 1990). Increasing row space from 17 cm to 30 cm and 45 cm progressively lowered lodging scores. However, this may have been due to wide rows producing less dry matter, as lodging was related to dry matter production of the crop at anthesis (flowering). Despite this trend, the wide rows (45

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[1] © Department of Agriculture and Food, Western Australia (2007), 26 April, 2013.

cm) had 10% less grain yield than the narrower rows, although this was not statistically significant.

On the other hand wide, row spacings can also be a disadvantage during harvest, particularly in lupins. Wide rows can cause ‘compression’ into the header particularly for double density or quad knife guards travelling in the direction of the rows (see Riethmuller 2010) at high ground speeds, that could ‘push’ the crop ahead of the cutter bar and not cut as cleanly. The cut crop can also fall sideways out of the harvester front, as there is no crop beside the row to support it.

3.5 Improved grain quality of cereals

Grain quality in this monograph refers to the characteristics associated with delivery to the silo system for sale. This includes test weight, 1000 grain weight and screenings and grain protein concentration. Reported effects of row spacing on grain quality are limited and inconsistent.

Test weight

Some studies have found row spacing to not affect test weight (Teich *et al.* 1993; Paynter and Hills 2007; Chen *et al.* 2008a). Others have found test weight to be affected, although findings were often inconsistent between experiments, and sometimes within experiments (McLeod *et al.* 1996; Amjad and Anderson 2006; Blackwell *et al.* 2006).

Grain size and grain size distribution

Grain size and grain size distribution are typically measured as 1000 grain weight and screenings. Screenings are defined as that portion of the grain that passes through a 2 mm sieve. Reports for the effect of row spacings on 1000 grain weight and screenings follow a similar pattern to those for test weight. Some reports have found row space to not affect 1000 grain weight (Fischer *et al.* 1976; Ridge 1981; Tompkins *et al.* 1991a; Teich *et al.* 1993; McLeod *et al.* 1996; Xie *et al.* 1998; Chen *et al.* 2008a), while others have reported wider rows decreasing screenings in barley (Paynter and Hills 2007) and increasing 1000 grain weight in wheat (Yunusa *et al.* 1993; Turner *et al.* 1994). Amjad and Anderson (2006) reported increased screenings at wider row spacings in one of five experiments; they did not report any differences in the remaining experiments nor any differences in 1000 grain weight.

A positive effect of wide row sowing on grain size would be expected where wide rows slow dry matter accumulation and reduce pre-anthesis water use, conserving water for later grain fill.

Grain protein

The situation for grain protein is similar to that for test weight. Some studies have found row spacing to not affect grain protein (Puckridge and Donald 1967; Tompkins *et al.* 1991a; McLeod *et al.* 1996; Chen *et al.* 2008a). Others have found significant positive and negative effects (Blackwell *et al.* 2006; Paynter and Hills 2007), or results have been inconsistent between experiments (Amjad and Anderson 2006).

3.6 Compatibility of machinery and farming systems

In Queensland and northern NSW, sorghum is the main summer crop with planting configurations commonly multiples of 1 m (Butler *et al.* 2003; Whish *et al.* 2005; Collins *et al.* 2006). In northern NSW sowings at 75 cm row spacings are also recommended in high yielding areas (Serafin *et al.* 2011). Row spacings of 75 cm and 100 cm are commonly recommended for summer crops. Row spacing traditionally used in wheat has not been compatible with those used for summer crops and farmers in northern farming regions have been interested in widening the row spacing used for wheat to 37.5 cm or 50 cm for greater compatibility with machinery and stubble row arrangement in the field (Buck *et al.* 2006).

In wheat growing areas more generally, the advent of air seeders has allowed farmers to sow with implements such as chisel ploughs and cultivators. These are fitted with tines with high breakout pressures and a greater spread between ranks of tines for improved stubble clearance. Thus, they are well suited to direct drilling into retained stubble. However, these implements typically have row spacings of 25 cm to 30 cm, and have reduced the options of farmers in choosing narrower row spacing (NA Fettell pers comm).

3.7 Wide rows and fertiliser related effects

Widening of row spacing implies an increase in fertiliser input per metre of row and, if fertiliser is in contact with seed, it may adversely affect germination and emergence. The trend in conservation tillage is to sow using narrow points or a disc seeder, further increasing the contact between fertiliser and seed. The damage to germinating seeds or seedlings can be from salt concentrations, phosphorus (P) toxicity, ammonia (NH_3) volatilisation or ammonium (NH_4^+) toxicity. The major mechanisms of damage are osmotic effects and ammonia production from nitrogenous (N) fertilisers (Dowling 1998). These can be modified by soil texture, moisture content, soil pH and crop species.

A secondary effect of wide rows is that widely spaced bands of fertiliser can be of limited accessibility for subsequent crops, particularly if these crops are sown in the inter-row space of the original crop.

Fertiliser toxicity

Traditional sowing systems used row spacings of about 18 cm and relatively wide sowing points; aiming for full soil disturbance. Seed and fertiliser spread within the row of these systems is estimated to be about 7.5 cm. In conservation farming systems where row spacing has been widened, and soil disturbance by sowing tines has been reduced using narrow points, seed spread within the sowing ribbon of 2.5-5.0 cm is typical (Rainbow 2000). Both these changes increase the contact between seed and fertilisers and the concentration of fertiliser within the sowing row.

The osmotic effects of a fertiliser depend on its formulation and underlying chemistry estimated in Table 2 (Rader *et al.* 1943; Mortvedt 2001). The salt index (SI) of a fertiliser is defined as the increase in osmotic pressure of the salt solution produced by a fertiliser as percentage of the osmotic pressure of the same weight of sodium nitrate ($NaNO_3$). This can be adjusted to give the osmotic pressure for the same weight of nutrient (Table 2).

Table 2 Salt index values for various fertiliser products and their nutrient inputs.

	Salt index		
Fertiliser and analysis	For equal weights of products (after Rader *et al.* 1943)	For equal weights of products (after Mortvedt 2001)	For equal weights of nutrient (after Mortvedt 2001)
		Nitrogen	
Sodium nitrate (17%N)	100	100	100 per unit of N
Ammonium nitrate (34% N)	105	104	52
Ammonium sulfate (21% N)	69	68.3	55.3
Urea (46% N)	75	74.4	27.5
		Phosphorus	
DAP (18% N, 20% P)	34	29.2	24.8 per unit of P
MAP (11% N, 23% P)	30	26.7	19.7
Triple super (20% P)	10		14.5*
Single super (9.1% P)	8		13*
		Potassium	
Potassium chloride (51.5% K)	114	120.1	39.6 per unit of K
Potassium sulfate (41.5% K)	46	42.6	17.5

*From Rader *et al.* (1943)

The SI does not predict the amount of fertiliser product that may reduce crop emergence, but compares fertiliser formulations. It shows which fertilisers would be most likely to damage germinating seeds if placed in the seed row. Generally, the N and potassium (K) products have higher SI values than the P fertilisers (Table 2) and are more likely to damage germinating seeds or seedlings.

Fertilisers containing NH_4^+ (for example, MAP, DAP, ammonium nitrate or sulphate), or which produce NH_4^+ (urea; Figure 4), can reduce seed germination and damage seedling development through osmotic effects, and through the production of NH_3 in alkaline soils. Ammonia, both in its gaseous and aqueous forms can be toxic to crops. Ammonium is adsorbed onto the cation exchange sites of the soil or it is converted to nitrate or NH_3. An equilibrium exists in soil between adsorbed NH_4^+, NH_4^+ in solution and NH_3 in gaseous and aqueous form (Figure 4).

Figure 4 suggests that seed and granules of fertiliser can be scattered in the row in a random manner. It follows from this that some seeds will be close to granules, and may be killed or damaged by osmotic effects or ammonia toxicity, while other seeds may be more remote from the granules. This suggests that even at very low fertiliser rates, when fertiliser is sown with seed, there is a loss of seedlings, although the loss may be small. There would then be an approximately linear relationship between fertiliser rate and seedling establishment, and only the slope of this relationship would change with crop species and fertiliser type. This linear relationship is supported by the data of Gelderman (2008).

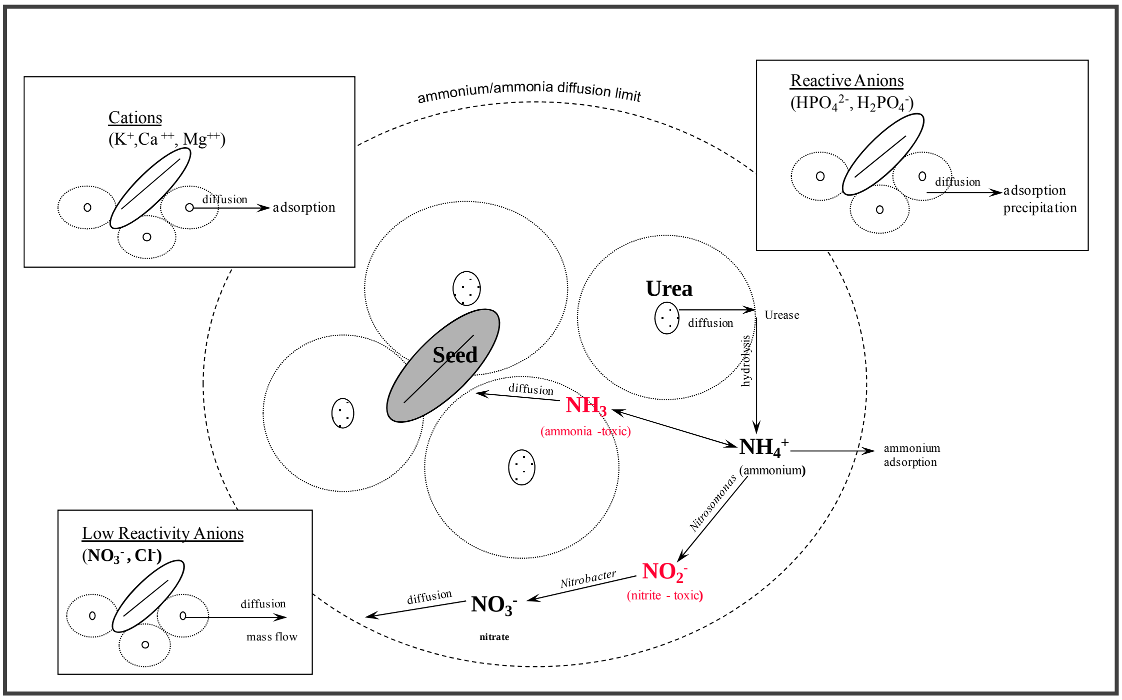

Figure 4 Pathways of toxicity to germinating seeds (From Dowling 1998), reprinted with permission of the author[2].

The adverse effects of fertiliser bands depend on the distance between the seed and fertiliser granules (Zhang and Rengel 1999). These gradients are also temporally variable. In a glasshouse study using DAP and urea, Zhang and Rengel (2002) described the gradients of pH_{Ca}, electrical conductivity (EC) and NH_4^+ concentrations in vertical slices of soil in relation to the placement of seed of wheat at 14, 42 and 63 days after sowing. With the 1 cm displaced treatment the greatest values of pH_{Ca}, EC, NH_4^+ and P (Colwell P) in the soil slice where the seed was located were recorded at day 14 and dissipated with time. Where fertiliser was displaced by 2.5 cm the effects peaked at lower values (pH_{Ca}, NH_4^+) on day 14, or peaked at lower values and later; EC and P peaked at day 63.

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[2] © Chris Dowling (1998), 10 July, 2013.

Other possible factors related to fertilisers

In conventional farming systems in Australia P toxicity has been reported in cereals using single superphosphate at 165-220 kg/ha, particularly when grown on sandy soils (Loneragan *et al.* 1966). Under such a conventional farming system row spacing would have been about 18 cm. Later glasshouse studies, using solution culture, showed that seedlings of wheat grew out of this toxicity if the P concentration in the solution was lowered (Bhatti and Loneragan 1970).

Superphosphates from two different sources differentially affected the emergence of wheat and oats (*Avena sativa* L.) when applied in contact with the seed (Kinra *et al.* 1962). The elevated water soluble fluorine content of one product (0.44% *cf* 0.15%) was considered the most likely cause of damage to seedling emergence. Biuret, produced in the manufacture of urea, can also be a damaging contaminant in fertiliser (Mikkelsen 1990).

Crops vary in their tolerance of different fertiliser products (Table 3). It is notable in this table that wheat and barley tolerate contact with urea well, while canola is among the most sensitive species.

Table 3 The ranking of plants for their emergence when in the seed row with urea (most tolerant = rank 1). The index was the % change in plant emergence for every 1 kg/ha of N addition as urea (after Gelderman 2008).

Rank	Crop	Index	Rank	Crop	Index
1	Maize	-0.50	9	Lentil	-1.40
2	Barley	-0.62	10	Mustard	-1.50
3	Wheat	-0.74	11	Safflower	-1.64
4	Durum	-0.76	12	Cotton	-1.65
5	Pea	-0.77	13	Soybean	-1.72
6	Oats	-0.84	14	Canola	-2.30
7	Sunflower	-1.17	15	Lucerne	-3.29
8	Sorghum	-1.30	16	Flax	-3.72

Seedbed utilisation (SBU) has been used widely to assist management of fertiliser toxicity induced by the use of wider rows and narrower sowing bands. SBU is the percentage of the seed bed potentially occupied by the crop (Desbiolles and Kleemann 2003). Where seed and fertiliser are applied in the same band, it also describes the likely distance between seeds and fertiliser granules. SBU is derived from the row spacing and the seed spread within the sowing row (Rainbow 2000).

$$SBU\% = \left(\frac{spread\ cm}{row\ space\ cm}\right) * 100$$

Recommendations for the maximum rate of fertiliser application in contact with wheat seed under adequate soil moisture conditions are available (Table 4; Rainbow and Slee 2004; Anon 2011b; Gelderman 2012). Canola can be even more sensitive than wheat to N fertiliser placed with the seed.

Table 4 Approximate safe rates of nitrogen (kg/ha) as urea sown in contact with the seed of wheat for soils of various textures with different seed bed utilisation (SBU; derived from Anon 2011b).

Point	Typical seed spread (mm)	Row space (cm)	SBU (%)	Soil texture	
				Sandy loam	Loam-clay
65 mm shear	50	18	28	40	50
Spear point	25	18	14	20	25
Spear point	25	30	8	11	22

All studies and recommendations reviewed for this monograph agreed that lowering the SBU% reduced the amount of urea that could be placed safely in contact with seed, and that canola was more sensitive than wheat to damage from urea (Figure 5). However, despite all reports assuming adequate soil moisture, there was a range in the maximum safe amount of urea N. In the wheat data, the research of Dowling (1998) and Anon (2011c) tended to estimate lower safe maxima than in other studies, although this was not so evident in the canola data. At an SBU of about 10%, typical of wider row spacing and narrow sowing points, the maximum safe rate of N as urea for wheat ranged from about 10-20 kg/ha N for light textured soils, 15-30 kg/ha for medium textured soils, and 15-40 kg/ha N for heavy textured soils. The maximum safe rate of nitrogen placed with canola seed was 0-5, 5-12 and 5-20 kg/ha of N as urea for soils of the same textures.

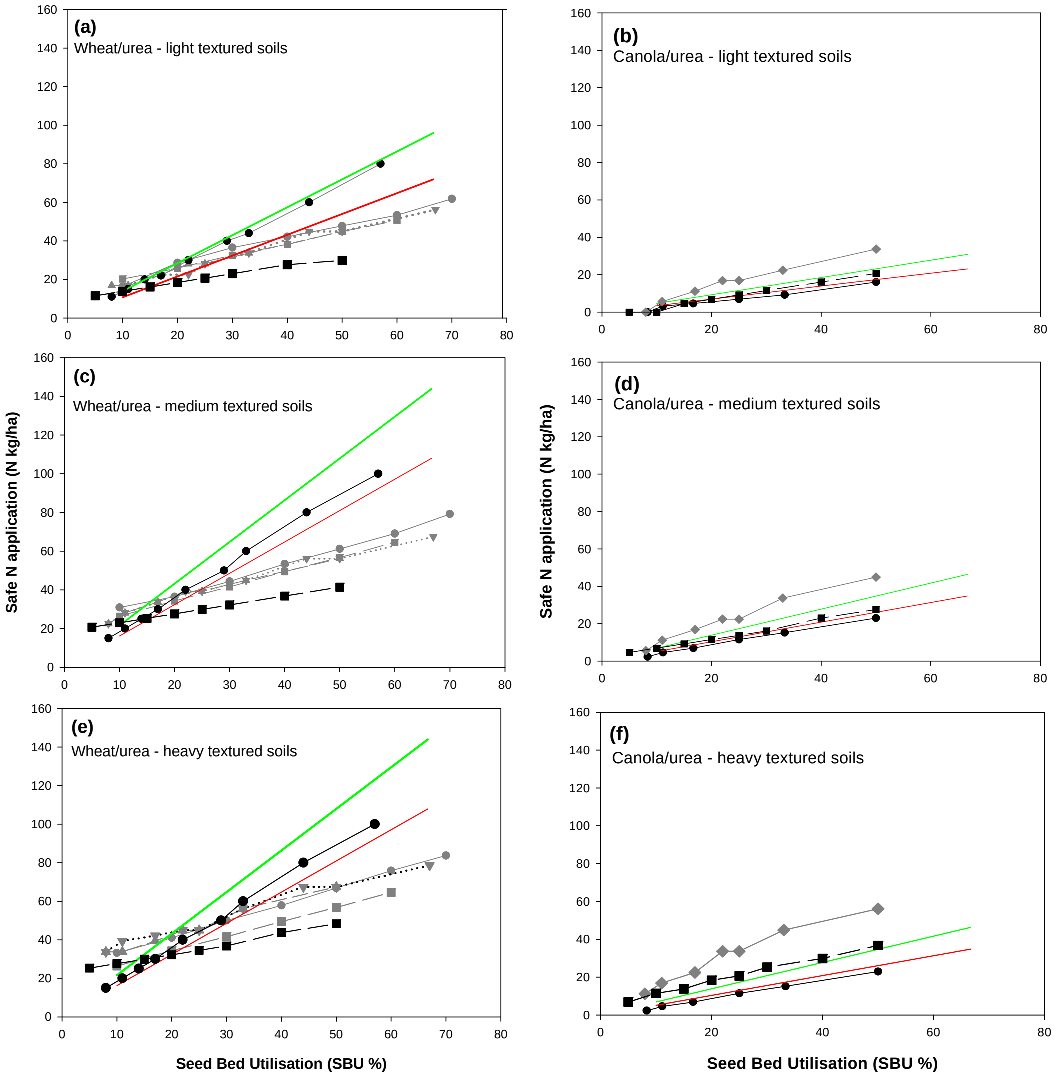

Figure 5 The relationships between the maximum rate of application for urea for satisfactory seedling emergence (expressed as kg/ha of nitrogen), and SBU% for wheat (a, c and e) and canola (b, d and e), suggested by Canadian authors [grey lines and symbols; —●— Harapiak (2008); — ■ — Harapiak and Flore (1993; 1995); — ▲ — Roberts and Harapiak (1997); ·····▼····· Anon (2002)], Australian authors [black lines and symbols; —●— Rainbow and Slee (2004), Anon (2011b); — ■ — Dowling (1998), Anon (2011c)] and USA authors [coloured lines, —— 15% emergence loss, —— 20% emergence loss; Gelderman (2007, 2008, 2009, 2012)].

The Canadian data presented in Figure 5 appeared to be the same recommendation, modified only slightly over time. It may well have been based on 32 experiments on wheat and barley across a range of soil types and field moisture conditions, or at least a subset of these data for wheat under adequate moisture conditions (cited by Harapiak and Flore 1995). It was likely that summations of these data assumed a loss of 15% of seedlings, as the mean data across the 32 experiments was presented in this manner, and delayed maturity was identified as a concern where seedling loss was higher than about 15% (Harapiak and Flore 1995).

Some Australian data (Rainbow and Slee 2004; Anon 2011b) repeated recommendations where the underlying source of the data was not described, other than to refer to ‘Australian and Canadian tolerance models’. Dowling (1998) carried out research on N fertilisers in contact with a range of crop types on alkaline soils, and integrated the results into a model 'Fertsafe'. This model was used to produce 'look-up tables' (Anon 2011c) on which Figure 5 was based.

USA data were from a review of field data (Gelderman 2007), and subsequent investigations using flat beds of medium textured soil in a glasshouse with a range of crops and fertiliser products (Gelderman 2008). The data were modelled to predict the seeding loss of various combinations of plant species sown in contact with a range of fertilisers (Gelderman 2009, 2012).

There were differences in the apparent toxicity of urea, MAP and DAP fertilisers in seed contact between references (Table 5).

Table 5 Comparisons of the maximum safe rate of N in DAP and MAP for wheat and canola relative to N in urea (100%), derived from three sources.

References	Urea (%)	MAP (%)	DAP (%)
Wheat			
Rainbow and Slee (2004), Anon (2011b);	100	100	100
Gelderman (2007, 2008, 2009)	100	85	104
Anon (2011c)	100	44	56
Canola			
Rainbow and Slee (2004), Anon (2011b);	n.a.[A]	n.a.	n.a.
Gelderman (2007, 2008, 2009)	100	110	111
Anon (2011c)	100	48	56

[A] recommended no nitrogen in seed contact with canola

Rainbow and Slee (2004) and Anon (2011b) suggested that the maximum amount of nitrogen that can be added in seed contact was the same for urea, MAP and DAP.

Gelderman (2007, 2008, 2009) identified only small differences between these N fertilisers, with the maximum safe rate of N as MAP being only 85% of that recommended for urea N. The results of Dowling (1998), as presented by Anon (2011c), showed a dramatic reduction in the safe amount of N as DAP or MAP, about half, compared with nitrogen as urea. The data reported in Table 5 does not support suggestions that DAP is more likely than MAP to cause establishment damage (Moody *et al.* 1995). However, the research of Dowling (1998) indicates greater damage from DAP than from MAP at equivalent N rates, while the derived table (Anon 2011c) does not.

The above recommendations on maximum fertiliser placed with seed were described for adequate soil moisture. Frequent recommendations have been made to halve these rates under dry conditions (Harapiak and Flore 1995; Harapiak 2008; Gelderman 2009; Anon 2011b, 2011c). Roberts and Harapiak (1997) gave some contrasts for emergence in moist and drier soils for wheat and canola with 66 kg/ha of N as urea in seed contact.

Other nutritional implications of wide row spacing

Using wide row spacings can potentially delay the ability of crops to grow roots into the inter-row space and exploit nutrients and water. This is despite the effects on plants in wide rows, at higher densities per metre of row than in narrower row spacings, to grow roots more rapidly into the inter-row space. This forced lateral root growth was illustrated for a range of crops at Meckering, WA during 2003 (Bowden and Scanlan 2004) where different crop species grew roots into the inter-row space at different rates (Table 6).

Table 6 The effect of high plant density in the crop row on sideways exploration of the inter-row space compared to single isolated plants, at two sampling times (from Bowden and Scanlan 2004), reprinted with permission[3].

	July 9, 2003		July 17, 2003	
	High density row	Single plant	High density row	Single plant
Species	Sideways exploration (cm)		Sideways exploration (cm)	
Lupin	29	16	40	27
Canola	29	15	51	30
Faba bean	25	17	25	19
Field pea	17	15	29	24
Chickpea	14	10	21	17
Wheat	na	14	30	na

Bowden and Scanlan (2004) used modelling to suggest that lupins sown in wide rows (50 cm row spacing) may not fully utilise nutrients located in the surface soil of the inter-row space where surface soil drying occurred in some seasons. Wide row spacing under these conditions made nutrients unavailable for plant growth where these nutrients would have greater availability if the crop was sown at a narrower row spacing.

Subsequently, the 'ROOTMAP' model was used to simulate the root growth of lupins and P uptake for a deep yellow sandy soil from Moora, WA (Chen *et al.* 2008b). Model runs indicated the importance of P fertiliser located with the seed as this reduced competition for soil P and encouraged root growth. However, the possibility of damage from root-fertiliser contact, particularly at wide row spacings (50 cm), led to suggestions that some P could be applied with the seed and additional fertiliser either banded away from the seed row or deep banded below the seed row for later access. Lateral displacement of the fertiliser band lowered plant uptake of P with an 8 cm displacement reducing uptake to about 60% of the uptake with fertiliser in seed contact. With a displacement of 23 cm laterally the uptake of P was further reduced to 30% of that of P fertiliser in seed contact. This observation has implications for subsequent crops sown in the inter-row. If sown again at a 50 cm spacing then the residual effect of the prior fertiliser would be reduced as the residual band would be about 25 cm from the new seed row. This could be extrapolated to trace elements

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[3] © Grains Research and Development Corporation, Canberra, ACT (2004), 24 June, 2013.

such as zinc (Zn) and manganese (Mn) which, like P, are immobile in the soil. This would reduce a new crop's access to trace elements applied with a previous crop.

The general development of a horizontal stratification of some nutrients also has implications for testing soils for nutrient availability. In systems with no cultivation where inter-row cropping is used the question of whether to take random samples or to sample the inter-row between the stubble rows is valid and as yet these issues are unresolved.

Agronomic implications

The adoption of wide row sowing by farmers frequently requires seed and fertiliser to be placed separately at sowing to minimise the fertiliser toxicity effects. Fertiliser also has been placed below the seed, or below and to the side of the seed row. The importance of applying small amounts of P fertiliser with the seed for early growth has lead to suggestions of placing of a small quantity of fertiliser in contact with the seed, with additional fertiliser separated from the seed.

Wide row spacings and fertiliser in contact with pulses

Pulses have been overlooked in recommendations regarding placement of fertiliser in contact with seed. There are no current or widely circulated recommendations on the maximum rates of P fertiliser for use in the seed row with pulses in wide rows, other than peas, either in Australia (Anon 2011b, 2011a) or the USA (Gelderman 2009, 2012). In Australia, lupins are the dominant pulse crop by area and production (Anon 2012), and there are no recommendations or guidance on management of P fertilisers in contact with seed, although wide row spacing is recommended in WA.

Mason *et al.* (1996) suggested a maximum of 16 kg/ha of P (as either single, double or triple superphosphate) be placed with the seed for lupins sown in 18 cm rows. Riethmuller and Jarvis 1991 (cited by Riethmuller *et al.* 2008b) reported an emergence in the field of 78% for placing 17.7 kg/ha of P (as double superphosphate) in the seed row compared with fertiliser placed 7 cm below the seed, when using 38 cm rows. This would be equivalent to 12 kg/ha of P in seed contact for an estimated 85% emergence in the 38 cm rows.

More recently, in NSW, three experiments have provided some estimates (Table 7). The first two experiments were studies of P application rates where 30 cm and 25 cm row spacings were used, respectively. Plant establishment was measured and the P rate giving 85% of the plant density of the nil fertiliser treatment was interpolated. Both these experiments studied white lupins (*Lupinus albus* L.). The third study was of row spacing (25, 50 and 75 cm) with nil fertiliser and 5.3 kg/ha of P/ha, with three narrow-leaf lupin cultivars and three white lupin cultivars. The maximum P rate for 85% emergence was an interpolation between the two P rates for the 25 cm row spacing. The effect on establishment was consistent for both narrow-leaf lupins and white lupins. This third study derived maximum P rates for 85% emergence much lower than the other studies. One possible explanation was a drying soil after sowing.

Table 7 Estimated maximum P rates in seed contact for 85% emergence of lupins from three NSW sources using wider row spacings.

Site/year	Estimated SBU%	Max P rate; fertiliser	Source
Gilgandra, 2009	8%	7.2 kg/ha; trifos	Rohan Brill pers comm
Grenfell, 2010	10%	13 kg/ha; trifos	Bruce Ramsay pers comm
Merriwagga, 2011	10%	2.3 kg/ha; single super	Haskins (2011) and pers comm

3.8 Reduced plant population with wide rows

It has been observed frequently that crops sown in wide rows have reduced plant populations compared with those sown in narrower rows. These effects go beyond the effects of fertiliser damage from more fertiliser per metre of row, although the adverse effect of fertiliser was often not separated from the potential effect of reduced plant population resulting from wide row spacings.

In experiments where fertiliser was placed with seed it was not possible to isolate the effect of early plant competition in wide row spacings from the effect of fertiliser concentration in the rows. However, at four sites in WA Amjad and Anderson (2006) separated the fertiliser from the seed; P was deep banded and N was top-dressed. They observed a reduction in the population of wheat with increased row spacing (Table 8).

Table 8 The main effect of row spacing on population of wheat (plants/m^2), measured 4 to 6 weeks after sowing, at four sites in WA, where fertiliser was separated from seed at sowing (from Amjad and Anderson 2006), reprinted with permission[4]*.*

	Experimental sites			
Row spacing (cm)	Gibson 2000	Salmon Gums 2000	Lort River 2001	Salmon Gums 2001
18	126	150	217	169
24	100	141	197	168
36	100	120	163	143
LSD (P = 0.05)	14	7	19	7

Reduced emergence of faba beans and chickpeas in wide row spacing in SA has been noted by Long *et al* (2002). Reduced plant density, as early as full emergence, does not support inter-plant competition invoked to explain reduced plant density in high density rows (Table 9). The fertiliser (DAP), was placed below the seed but the separation distance was not given. In two faba bean experiments in WA there was no effect on plant density at full emergence with row spacings of 19 cm and 38 cm as P fertiliser was increased to 30 or 45 kg/ha (depending on experiment) whether the triple superphosphate was placed either with the seed or 4 cm below the seed (Bolland *et al.* 2001).

The loss of plants when sown in wide rows has led to suggestions that higher sowing rates could overcome lower plant populations. However, on examination it appears responses in yield to increased sowing rates of wheat are more likely with narrow row spacing, than with wide row spacing where the response has been anticipated (see later Table 12 and related text).

Table 9 Plant densities at emergence in SA at various row spacings (Long et al. 2002). Fertiliser was DAP at 100 kg/ha deep banded below the seed.

	Plant density (plants/m^2)	
Row spacing (cm)	Faba beans	Chickpeas
23	69	68
50	43	35
100	15	32
LSD (P = 0.05)	13	22

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[4] © CSIRO Publishing, Collingwood, Vic (2006), 24 April, 2013.

4. Row spacing and yield

4.1 General considerations

In high yielding environments yield is maximised through rapid groundcover by a newly sown crop. This maximises the capture of light and minimises evaporation from the soil surface. The pattern of root growth is likely to parallel that of the shoots and plant arrangements that deliver rapid groundcover are also likely to result in root systems that utilise the soil volume more fully, exploiting nutrients and water. Square planting arrangements have been proposed (Pant 1979), while hexagonal arrangements may show some advantage (Fischer and Miles 1973; Pant 1979). With wheat, Holliday (1963) demonstrated that square arrangements were preferable.

In Australia, a square pattern of plant arrangement was higher yielding in one of three experiments (Auld *et al.* 1983). The authors precision sowed seed by hand and later transplanted seedlings where any were missing. A square plant pattern (rectangularity = 1) was superior to arrangements of increased rectangularity where plant density was low (75 plants/m^2), but had no effect at a higher plant density (200 plants/m^2; Figure 6a). In two experiments with machine-sown crops, across a wide range of row spacings and sowing rates, Fawcett (1964, 1967) identified the same trend; at high plant densities (about 200 plants/m^2) there was less impact on yield with increased rectangularity than where plant densities were lower (Figure 6b and c).

Densities of wheat of 100-150 plant/m^2 have been recommended in northern NSW (Butler *et al.* 2003). At about this density (100 plants/m^2; about 45 kg/ha sowing rate; see Figure 6b), a 19 cm row space had an estimated rectangularity of about four, while widening rows to 28 cm or 38 cm increased rectangularity to eight or 16, respectively. This increase in row spacing reduced grain yield. At 200 plants/m^2 (a sowing rate of 90 kg/ha) a 19 cm row spacing had an approximate rectangularity of eight, and widening rows to 28 cm increased rectangularity to about 16, but reduction in grain yield was slight. Two issues were raised here, which are addressed elsewhere in this monograph. Firstly, there is the possibility that increasing row spacing beyond about 18 cm could reduce grain yield, and secondly, increased plant population could reduce, but perhaps not eliminate, any yield loss associated with widening rows. Of course, increasing sowing rate will increase the rectangularity of the plant arrangement at any row spacing.

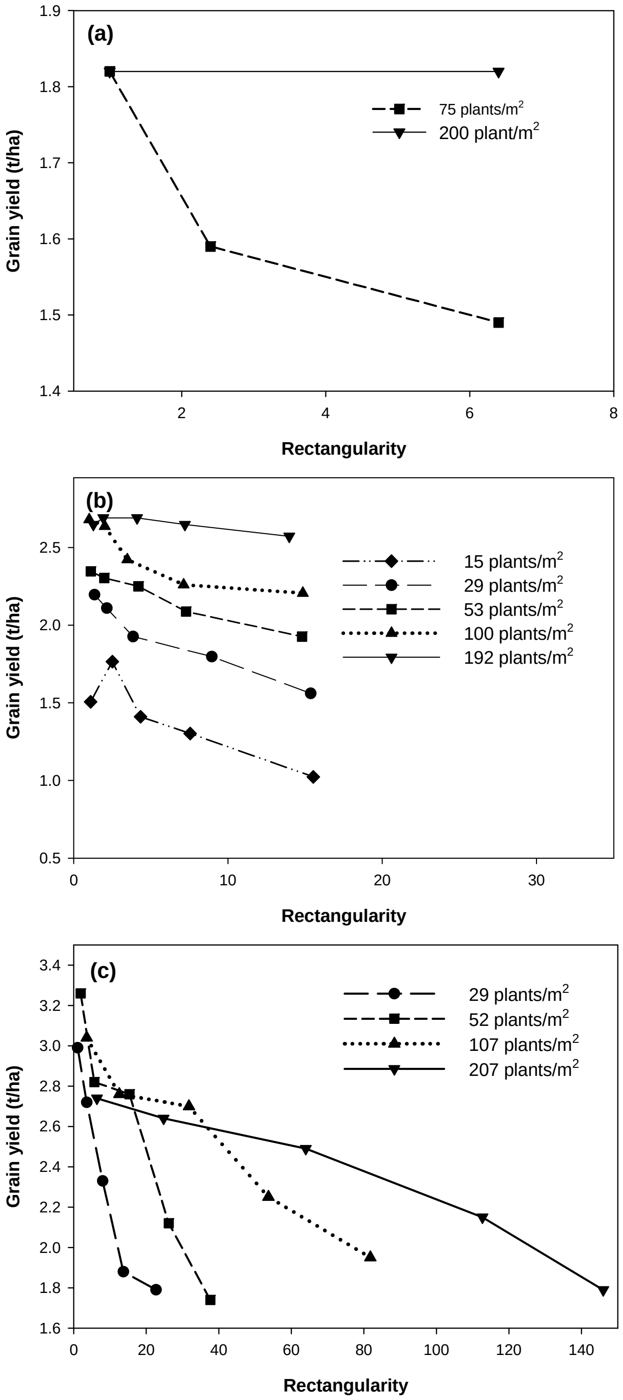

Figure 6 The yield of wheat with increasing rectangularity (ratio of distance between plants in two directions; distance between rows/distance of plants within rows) in precision-sown experiment at Orange, NSW (a; (Auld et al. 1983; Kemp et al. 1983), and in two machine-sown experiments at Narrabri, NSW (b and c; Fawcett 1964, 1967).

In addition to row spacing being either positive or negative in its effect on grain yield, there are inferences that could be made about the shape of the response in grain yield with increasing row spacing. These imply there could be an 'optimal' row spacing, suggesting increasing row spacing could increase grain yield initially, reach an 'optimum' and further increases in row spacing would reduce yield (for example, Smith *et al.* 1995; Zylstra 1998). Solie *et al.* (1991) tested three row spacings (7.5 cm, 15 cm and 23 cm) in wheat in Oklahoma, USA, and suggested the 'optimal' row spacing was 6.6 cm. Interestingly, the 'optimum' was below the narrowest row spacing tested and the shape of the response in yield to changes in row spacing may depend on the range of row spacings tested. The second inference is there is no effect of increasing row spacing on yield until a 'threshold' is reached, beyond which further increases in row spacing are associated with reduced grain yield (for example Peltzer *et al.* 2009). We have concluded from field data the yield loss (or gain) with row space increase is most often linear and this is discussed further in this monograph.

4.2 Grain yield reduced in many situations

When 18 cm row spacing remained common in Australian broadacre cropping the possibilities of either narrowing or widening row spacing were pursued. In WA, 9 cm row spacing was advantageous for yield of wheat in 10 of 12 experiments (Doyle 1988). The average yield increase with 9 cm rows compared with 18 cm rows was 15% (average yield increase of 0.204 t/ha). Row spacing wider than 18 cm reduced yield. Similar results were derived from data reported by Smith *et al* (1995) in SA; yield increased by 7% by narrowing 18 cm rows to 9 cm (averaged across 10 experiments) and declined by 5% when rows were widened from 18 cm to 36 cm (averaged across seven experiments). At Merredin in WA, across 10 seasons of a long term experiment, 9 cm rows compared with 18 cm row spacing increased wheat yield by 2% while widening rows to 36 cm decreased yield by 7% (Riethmuller 2004b). However, the usefulness of narrowing rows to 9 cm has been dismissed because of the cost of machinery modification and operation, and an inability to cope with retained stubble.

It would seem that widening rows beyond 18 cm can frequently reduce yield, yet farmers have adopted the practice. A detailed re-examination of Australian data is presented in the next section of this monograph.

4.3 Improved grain yield when water saved for grain fill

Wide rows slow production of biomass and delay canopy closure. The crop captures less radiation and more water is lost through evaporation from the inter-row soil surface (Eberbach and Pala 2005) rather than through transpiration, potentially limiting crop production.

However, in water limited and low yielding situations grain yield can increase at wider row spacings (Blackwell *et al.* 2006; Jones and O'Halloran 2006). With wider row spacings the availability of both nutrients and water in soil depends on the time required for roots to grow further from the row and access these resources in the inter-row space (Bowden and Scanlan 2004). This means water is ‘rationed’ to crops at wider row spacings, and less biomass is produced, allowing water to be conserved for use by the crop post anthesis. In water limited, low yielding environments this can be an advantage to crops sown at wide row spacings by conserving water for grain fill. Any water conservation for post-anthesis use would depend on the rate of evaporation from the soil surface being less than water use by the crop. Rates of evaporation from the soil surface vary considerably between soil types (French and Schultz 1984).

4.4 Australian data on row spacing in wheat

Few experiments on row spacing in wheat cover a wide range of row spacings. The few data sets that do (Fawcett 1967; Doyle 1980; Mead and Newell undated) show approximately linear responses in grain yield in relationship to row spacing (Figure 7a). Data averaged across a series of experiments also appears to be linear (Figure 7b, c).

The observation, that the response in grain yield with row spacing change is approximately linear, suggests the 'optimum' or 'threshold' is generally below the range of row spacing tested (ie < 9 cm; Figure 7). In reviewing numerous experiments on row spacing in wheat it was necessary to adopt an approach that

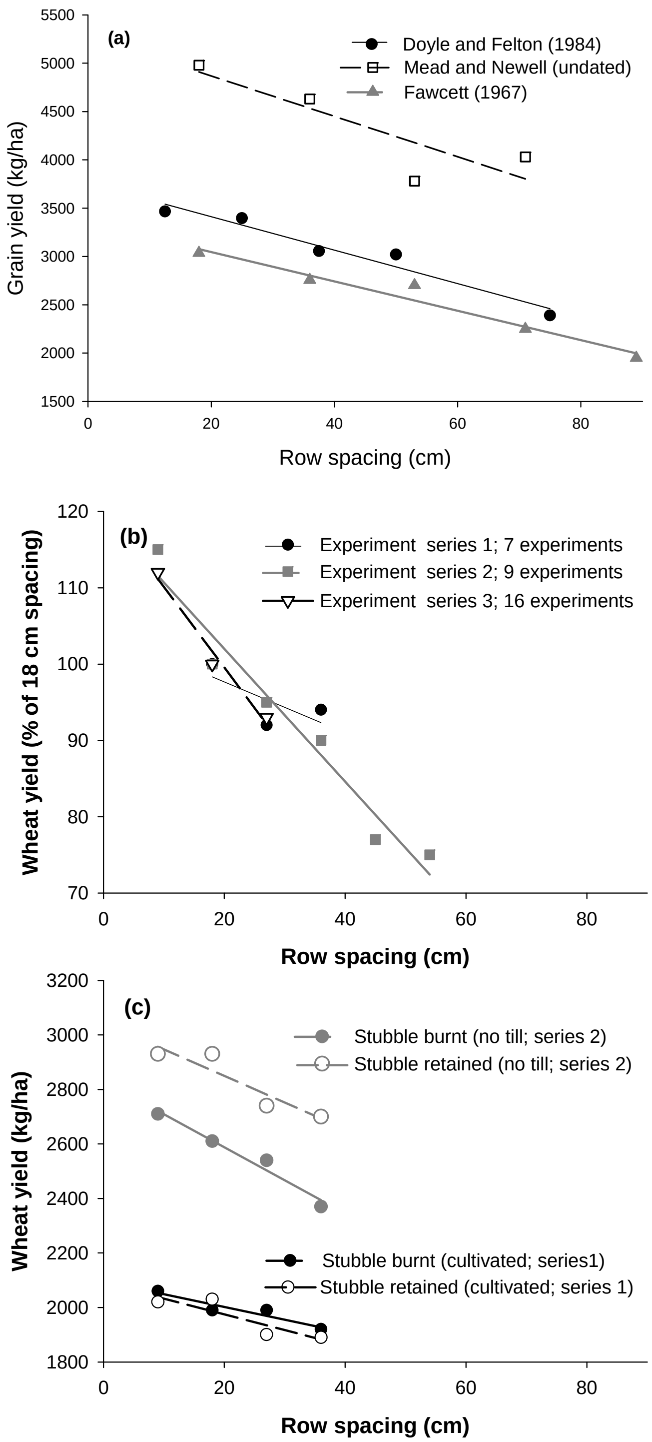

Figure 7 The relationship between row spacing and grain yield in wheat a) in three experiments covering a wide range of row spacings in northern NSW (Fawcett 1967; Doyle and Felton 1984) and central NSW (Mead and Newell undated); and b and c) data averaged across a series of seasons (Riethmuller cited by Anderson et al (2000), and Riethmuller (2004b), respectively).

utilised experimental data where the row spacings used often differed. In unifying the available data it was proposed that the response in wheat yield to changes in row spacing was approximately linear and linear responses were fitted to the data. Estimates of yield at a standard row space of 18 cm ($Yield_{18}$), and the rate of change of yield with deviations from this 'standard' spacing (kg/ha/cm of row space widening), were then derived values for each experiment.

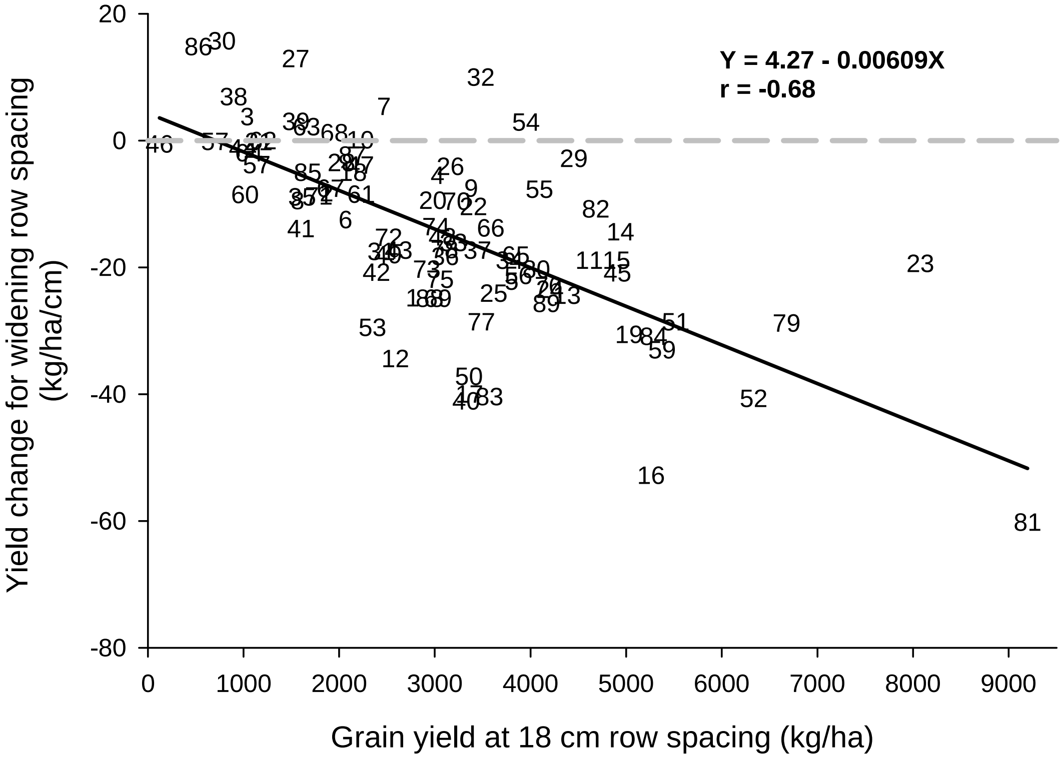

Figure 8 The relationship between grain yield at 18 cm row spacing and the rate of change in grain yield with row widening for 89 experiments on wheat in Australia. Data points are numbered and are further described in Appendix 1.

The data for 89 experiments available across Australia were used and yield change was related to yield at 18 cm row spacing ($Yield_{18;}$ Figure 8). Data presented in Figure 8 were restricted to experiments where the narrowest row spacing tested was 25 cm or less. This was to limit the extrapolation of the model too far beyond the data when estimating $Yield_{18}$. Of the 89 experiments presented 20 included a row spacing of 9 cm, while a further 12 included row spacing between 10 cm and 15 cm. A maximum row space of >35 cm occurred in 75 experiments, with 12 experiments having a maximum row space of ≥50 cm. Only five experiments had a maximum row space of 75 cm or more (Appendix 1). Figure 8 is best used in the range of 9 cm to 36 cm; that is a halving or a doubling of the standard 18 cm row space, although data exists at row spacings wider than this range.

The fitted line in Figure 8 indicates that at $Yield_{18}$ of less than 700 kg/ha, widening rows increases grain yield. At $Yield_{18}$ of 500 kg/ha, doubling row space to 36 cm increases yield to 520 kg/ha. At a $Yield_{18}$ of 2000 kg/ha, widening rows to 36 cm reduces yield to 1860 kg/ha, and at $Yield_{18}$ of 4000 kg/ha yield is reduced to 3640 kg/ha with 36 cm row spacing.

At a $Yield_{18}$ of 2000 kg/ha ***narrowing*** rows to 9 cm increases yield to 2070 kg/ha, and at $Yield_{18}$ of 4000 kg/ha yield increases to 4180 kg/ha. This supports the comments from WA (Doyle 1988) and comment on the European and American experience (see Smith *et al.* 1995) that narrowing of row spacing can increase yield. However, at $Yield_{18}$ of 500 kg/ha narrowing row to 9 cm would decrease to 480 kg/ha.

The variability of the data around the general relationship suggests climate, soil and/or agronomic management can have a large impact on the effect of row widening on yield. Also data may vary because they were derived data from a wide range of experiments, which used different experimental treatments and designs.

One set of data, from Merredin in WA, had a constant experimental design and 13 'experiments'; the experiment was repeated in different years on the same site. The design was four row spacings (9 cm, 18 cm, 27 cm and 36 cm) with two stubble management treatments (retained and burnt) in six replicates (Riethmuller *et al.* 2008a). In some years the plots were cultivated and in other years no-tilled (Riethmuller 2004b). The relationship for all sites is shown below with the data from Merredin highlighted (Figure 9). It is clear the Merredin data remains closer to the general relationship than much of the other data, suggesting the wide variability of data can be ascribed to variables associated with the design and implementation of the experiments. While the soil type was constant at Merredin, the agronomic practice changed between years and seasonal conditions, and grain yield varied.

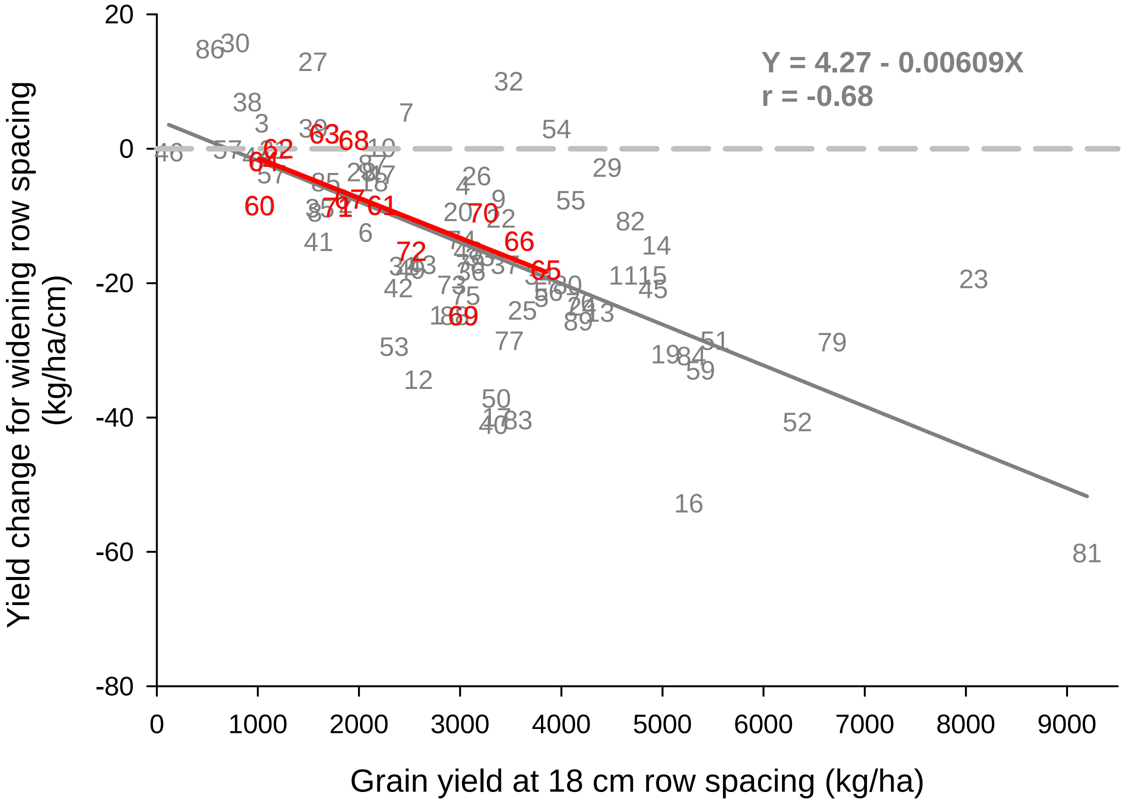

Figure 9 A representation of Figure 8 for the 89 sites (grey), with Merredin, WA data identified in red.

Most of the data presented in Figure 8 were derived from experiments in WA, SA and NSW. Only two experiments were presented from Victoria, and none from Queensland. Additional data from Victoria will be addressed later in this monograph (Jones and Desbiolles 2001; Jones and O'Halloran 2006; Jones 2007), while site specific data from Queensland were unavailable (Buck *et al.* 2006; Collins *et al.* 2006; Buck and Keys 2008). Inspection suggested the relationship in Figure 8 may vary between states and regions, so independent linear models were fitted for WA, SA and for central and southern NSW, and separately for northern NSW. However, while the relationships for the states and regions did not vary significantly (Figure 10), there was a trend in that the states with a Mediterranean climate (WA and SA) appeared to have a more rapid loss of yield with row widening than regions with non-seasonal rainfall (central and southern NSW) or summer dominant rainfall (northern NSW).

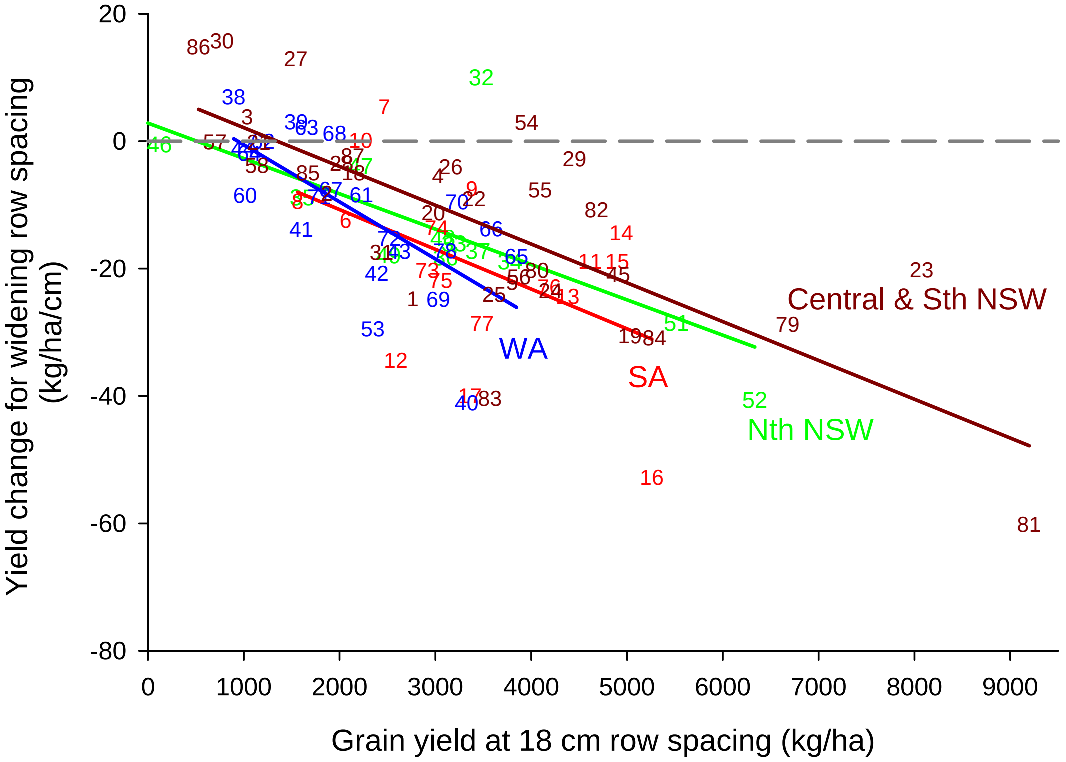

Figure 10 The relationships between yield of wheat at 18 cm row spacing and rate of change of yield with row space widening for 87 sites in WA, SA, Central and Southern NSW and Northern NSW.

4.5 Some international comparisons of data on row spacing in wheat

Australian data were compared to smaller sets of similar data from Canada and USA. Canadian data were drawn from a single paper covering 13 sites in western Canada and were derived from relationships within that paper (Tompkins *et al.* 1991b). The data presented the main effects of row spacing at 9 cm, 18 cm, 27 cm and 36 cm or 15 cm, 20 cm, 30 cm, 45 cm and 60 cm, depending on experiment, and were averaged across sowing rates and cultivars. The row spacing effects were fitted to linear relationships for categories based on environment and yield. Figure 11 reports the data in the manner used in this monograph.

Data for the USA were from a diverse set of environments and are detailed in Appendix 2 and presented in Figure 11. These data were highly variable, as were the Australian data. The USA data predominantly assessed the effects of narrower row spacing compared with a benchmark of about 18 cm spacing (Appendix 2).

While not an exhaustive exploration of data from Canada and the USA, the generalised response was consistent with the Australian experience; increasing row spacing beyond 18 cm decreased yield, and/or yield increased as row spacing was reduced to less than 18 cm. The rate of yield loss with row space widening was greater for the USA than for Canada or Australia. With a 3000 kg/ha yield at 18 cm row spacing, row widening gave yield losses of 42, 21 and 14 kg/ha/cm for USA, Canada and Australia, respectively. Neither the Canadian nor USA data showed any increase in grain yield with row widening at low *Yield*$_{18}$.

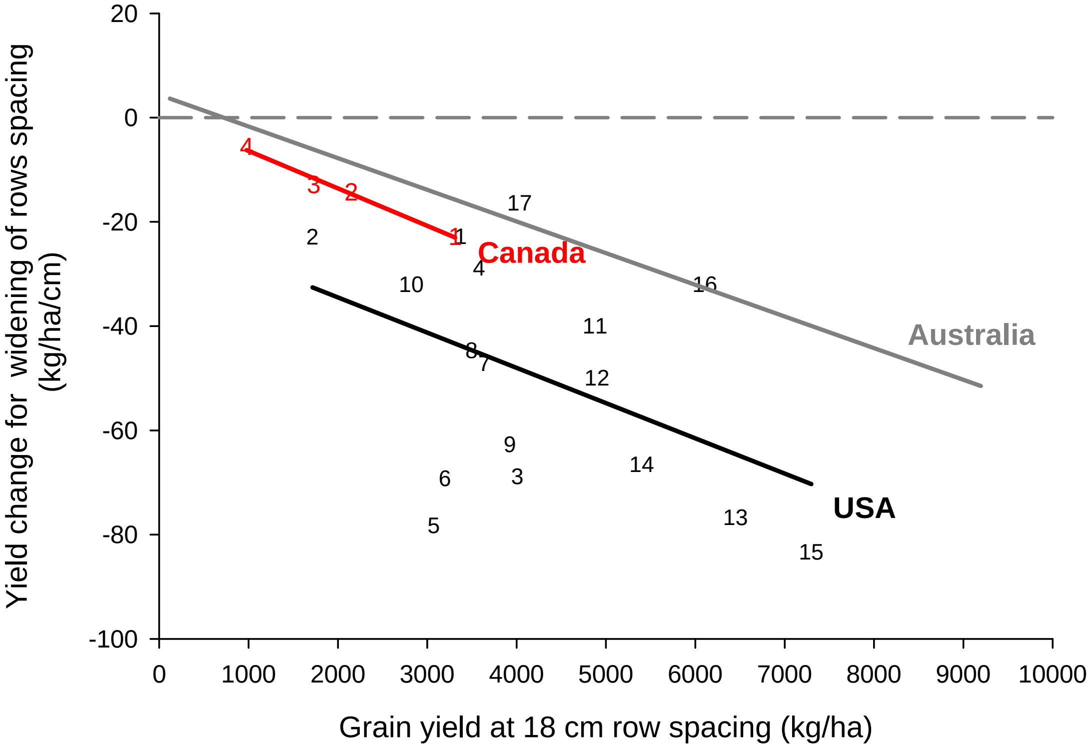

Figure 11 The relationship between grain yield of wheat at 18 cm row spacing and the rate of change of grain yield with row space widening in Australia (grey line; no data points shown), Canada (red; Tompkins et al. 1991b) and the USA (black line and data points; details of data in Appendix 2).

4.6 Very wide row spacing (> 36 cm) in wheat

Studies of very wide rows have been undertaken in Victoria (Jones and Desbiolles 2001; Jones and O'Halloran 2006; Jones 2007) and WA (Blackwell *et al.* 2006; Blackwell 2007).

The Victorian study was carried out in the Mallee and compared 33 cm and 67 cm row spacings across 36 experiments with wheat (Jones and O'Halloran 2006). In these experiments there was a confounding of sowing rate, N fertiliser and previous crop with row spacing (see Jones 2007). Wide rows were sown at 2/3 of the sowing rate of the 'narrow' rows (Jones and O'Halloran 2006). Despite this confounding and the necessary extrapolation beyond the range of the data, *Yield*$_{18}$ and slope were estimated and compared in Figure 12 to the previous Australian results given in Figure 8. The relationships were remarkably consistent, although there was a dominance of low yielding sites in the Mallee.

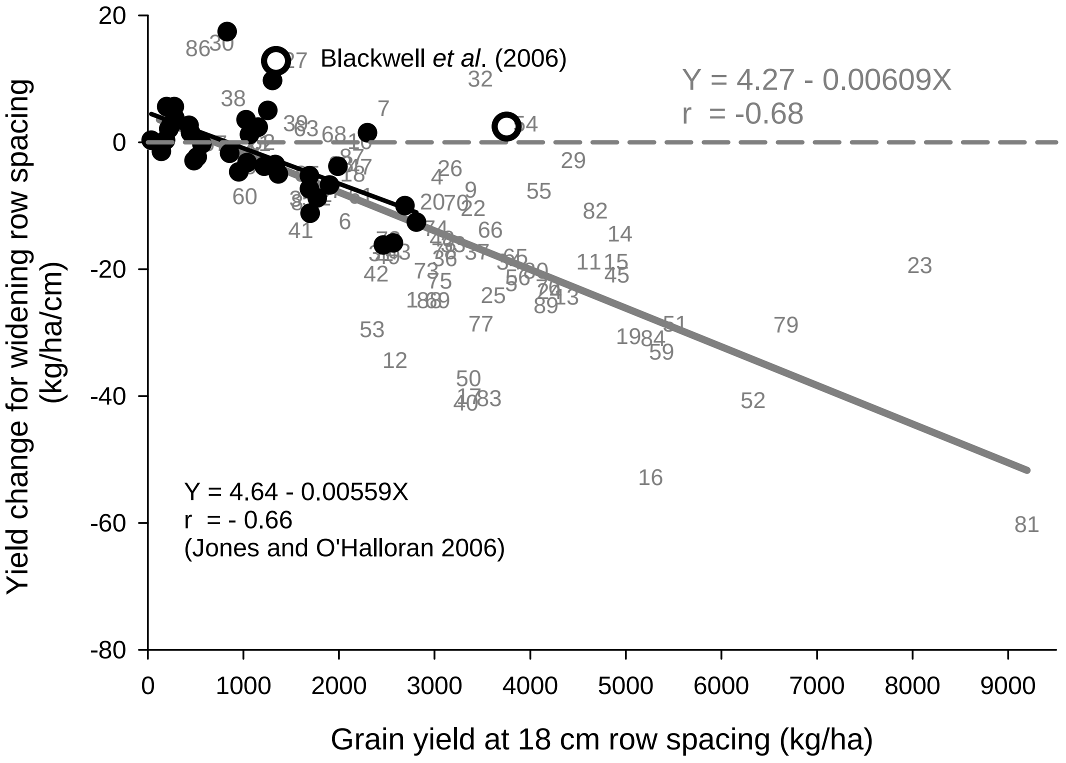

Figure 12 Data derived from experiments on very wide row spacings in wheat, from the Victorian Mallee (Jones and O'Halloran 2006; black solid circles, fitted line and equation), and from WA (Blackwell et al. 2006; open circles), overlaid on Figure 8 (grey numbers, fitted line and equation).

In WA a single experiment was held at Pindar in 2005 comparing 30 cm and 60 cm row spacings in wheat (*cv* Arrino) in dryland and irrigated conditions (Blackwell *et al.* 2006; Blackwell 2007). In both dryland and irrigated conditions grain yield was higher at 60 cm spacings (data averaged across two sowing rates). The higher yield under irrigation was unusual in giving yield increases with increased row spacing at relatively high yield (estimated *Yield*$_{18}$ of 3750 kg/ha). However, these data do not lie outside the variability apparent in the other Australian data (*cf* with sites 27 and 54).

4.7 Australian data on row spacing in barley

Only 18 experiments on row spacing in barley were identified (Appendix 3). Row space grain yield relationships were again approximately linear (Figure 13). The relationship was approximated well in all cases, with the possible exception of the highest yielding site at Parkes during 2008.

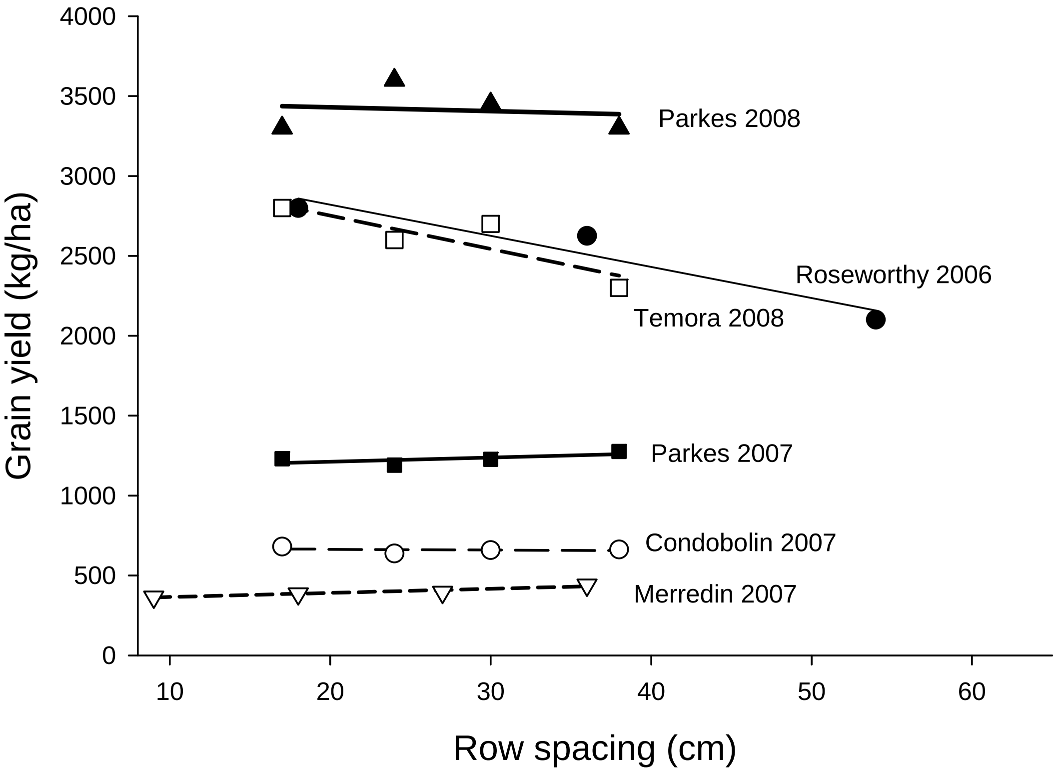

Figure 13 Some examples of grain yield and row spacing relationships for barley at Roseworthy, SA in 2006 (Kleemann and Gill 2008), Parkes and Condobolin, NSW in 2007 (Fettell 2008), Temora and Parkes, NSW in 2008 (Fettell 2009) and Merredin, WA in 2007 (Riethmuller et al. 2008a).

The rate of change of yield with changes in row spacing at a given *Yield*$_{18}$ were close to the relationship for wheat (Figure 14). This suggested wheat and barley were similar in their reaction to row space changes. With barley, yield increased with row widening at yields <1100 kg/ha.

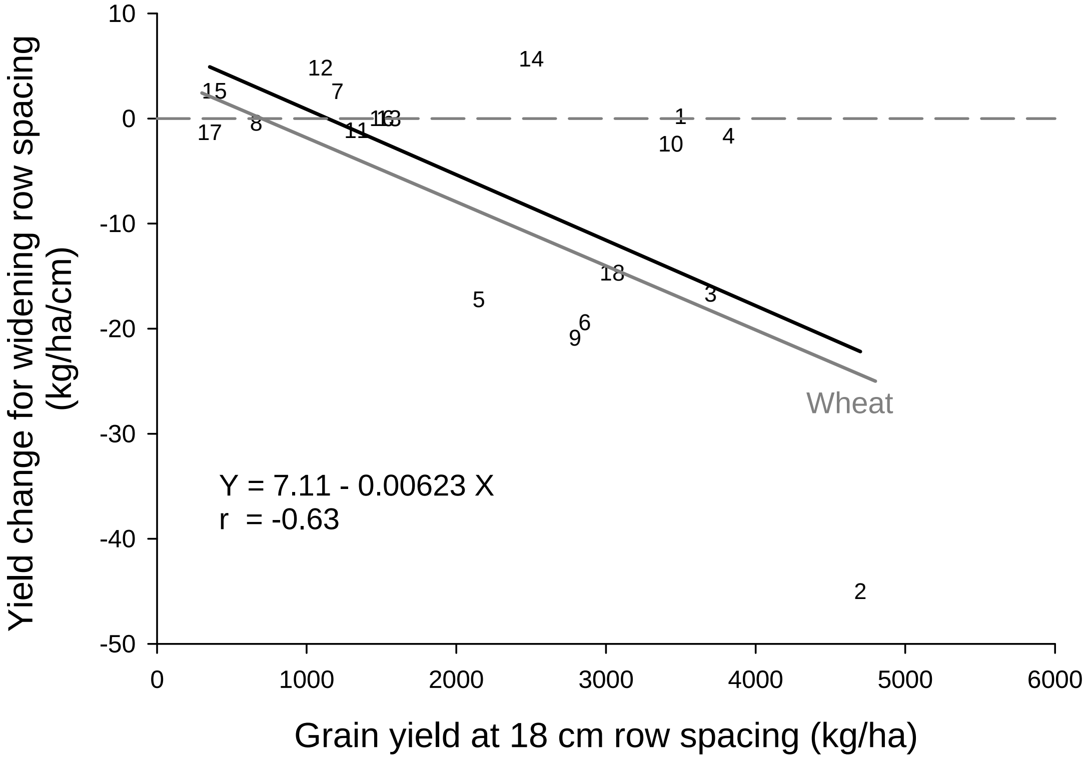

Figure 14 Relationship between yield of barley at 18 cm row spacing and the rate of yield change with further row widening in Australia (black data, line and equation; see Appendix 3 for site details). The grey line was the relationship for wheat from Figure 8.

4.8 Australian data on row spacing in canola

Thirty three experiments were identified that investigated row spacing in canola in Australia; 14 from WA, 13 from central and southern NSW, and three each from northern NSW and SA (Appendix 4). Again the relationships between row spacing and yield appear to be close to linear (Figure 15).

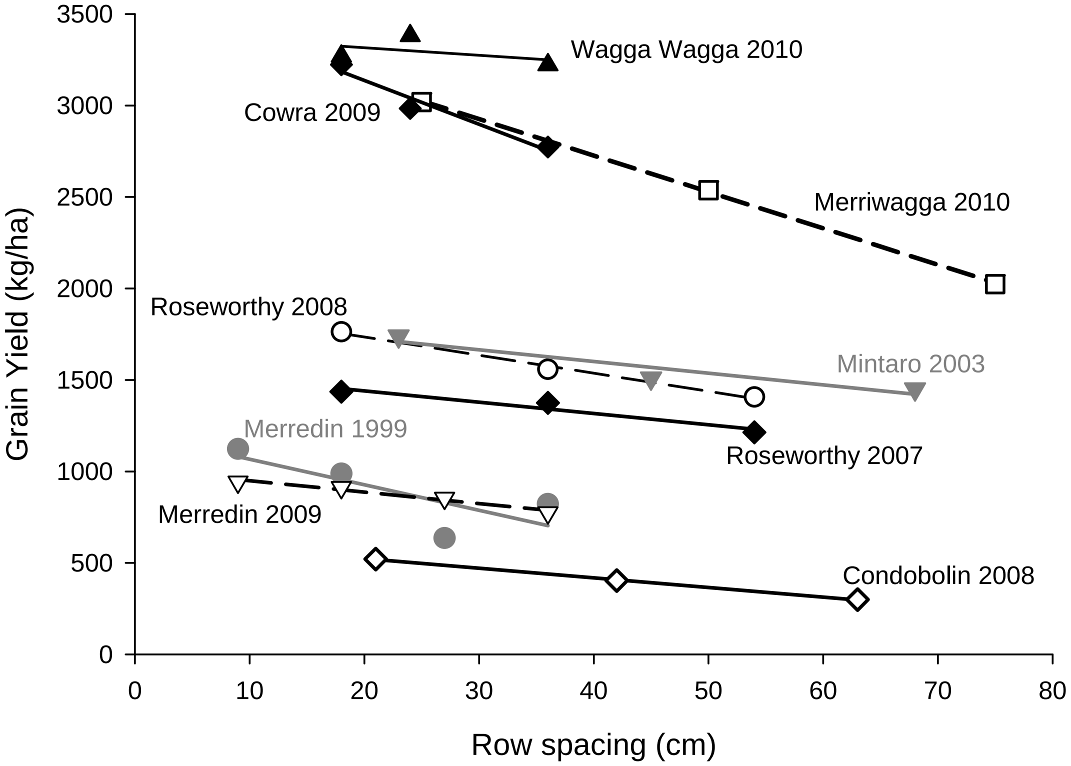

Figure 15 Some examples of grain yield and row spacing relationships for canola at Roseworthy, SA in 2007 and 2008 (Kleemann and Gill 2010a), Mintaro, SA 2003 (Anon 2004) , Merredin, WA 1999 and 2009 (Riethmuller pers comm) and Condobolin, NSW in 2008, Cowra, NSW in 2009 and Wagga Wagga, NSW and Merriwagga, NSW in 2010 (Martin et al. 2011).

The data were presented as the relationship between $Yield_{18}$ and the rate of yield change for each centimetre of row space widening (Figure 16) with separate relationships for WA and central and southern NSW. In both WA and central and southern NSW the canola yield declined with increased row spacing, and the rate of decline was greater as $Yield_{18}$ increased. The rate of decline was not significantly different between WA and central and southern NSW and similar to the relationship obtained for wheat (Figure 8). Data from SA was consistent with this general relationship.

The data from northern NSW appeared different, with yield either static or increasing as rows widened. Yield was reported as increasing at $Yield_{18}$ of 2000 to 2500 kg/ha. These data were reported by Felton *et al.* (2004), and yields from the weed free treatments are presented in Figure 16. Increased weed populations (triticale in this experiment as a surrogate for wild oats) reduced *Yield*$_{18}$ (that is the data points moved closer to the general relationship as weed populations increased).

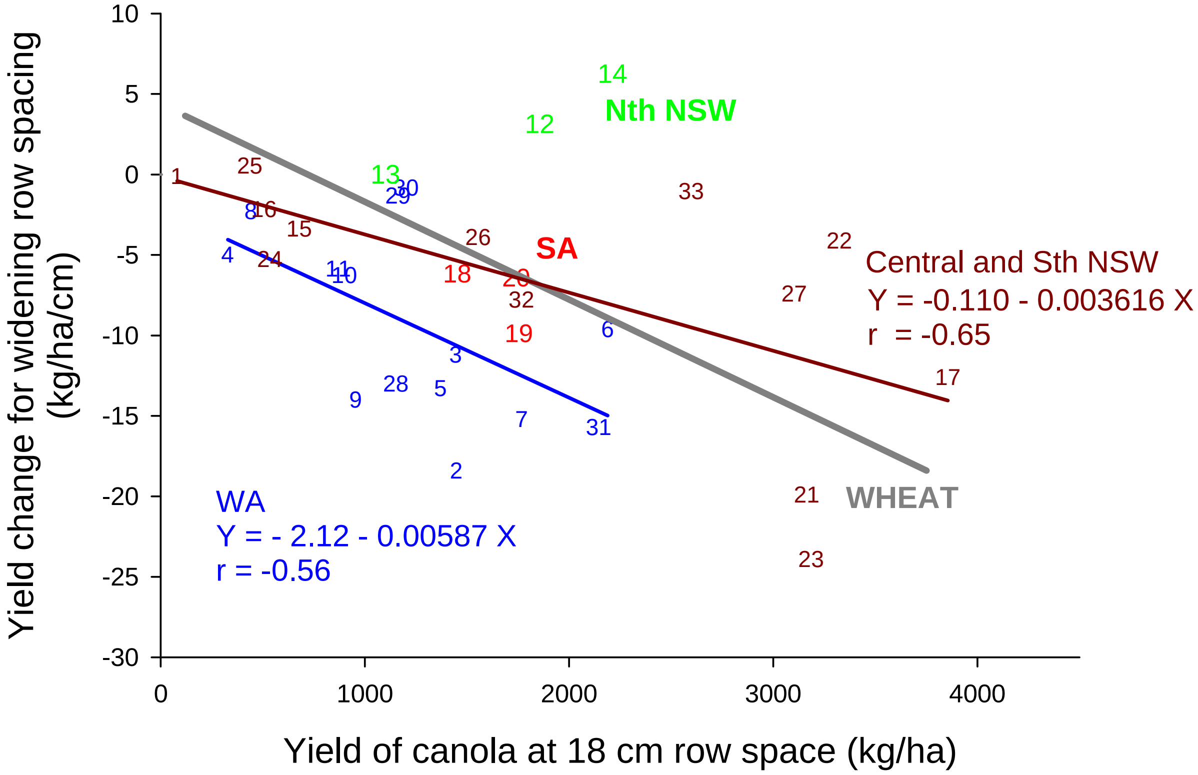

Figure 16 Relationship between yield at 18 cm row spacing for canola and the rate of yield change with further row widening in WA (blue) and central and southern NSW (dark red) with data points for SA (red) and northern NSW (green; see Appendix 4 for details). The grey line was the relationship for wheat from Figure 8.

4.9 Row spacing in narrow-leaf lupins

Data on narrow-leaf lupins were mainly from WA where 24 experiments were identified (Appendix 5). In NSW, 10 experiments were identified. Inspection of responses in WA of yield of lupin grain to increased row spacing did not appear to be exclusively linear. The 'curve' in the response data suggested that in some experiments lupin yield remained unaffected or increased as row spacing was increased initially (from about 18-25 cm to 36-50 cm), and with further row spacing widening yield appeared to decline (from about 42-50 cm to about 100 cm; Figure 17). This was observed in several reports in relation to individual experiments (Fosbery *et al.* 2003; French and Wahlsten 2003; Harries *et al.* 2003), and has been generalised as wide rows being recommended for northern and central cropping areas of that State, and not for southern areas (Harries and French 2007).

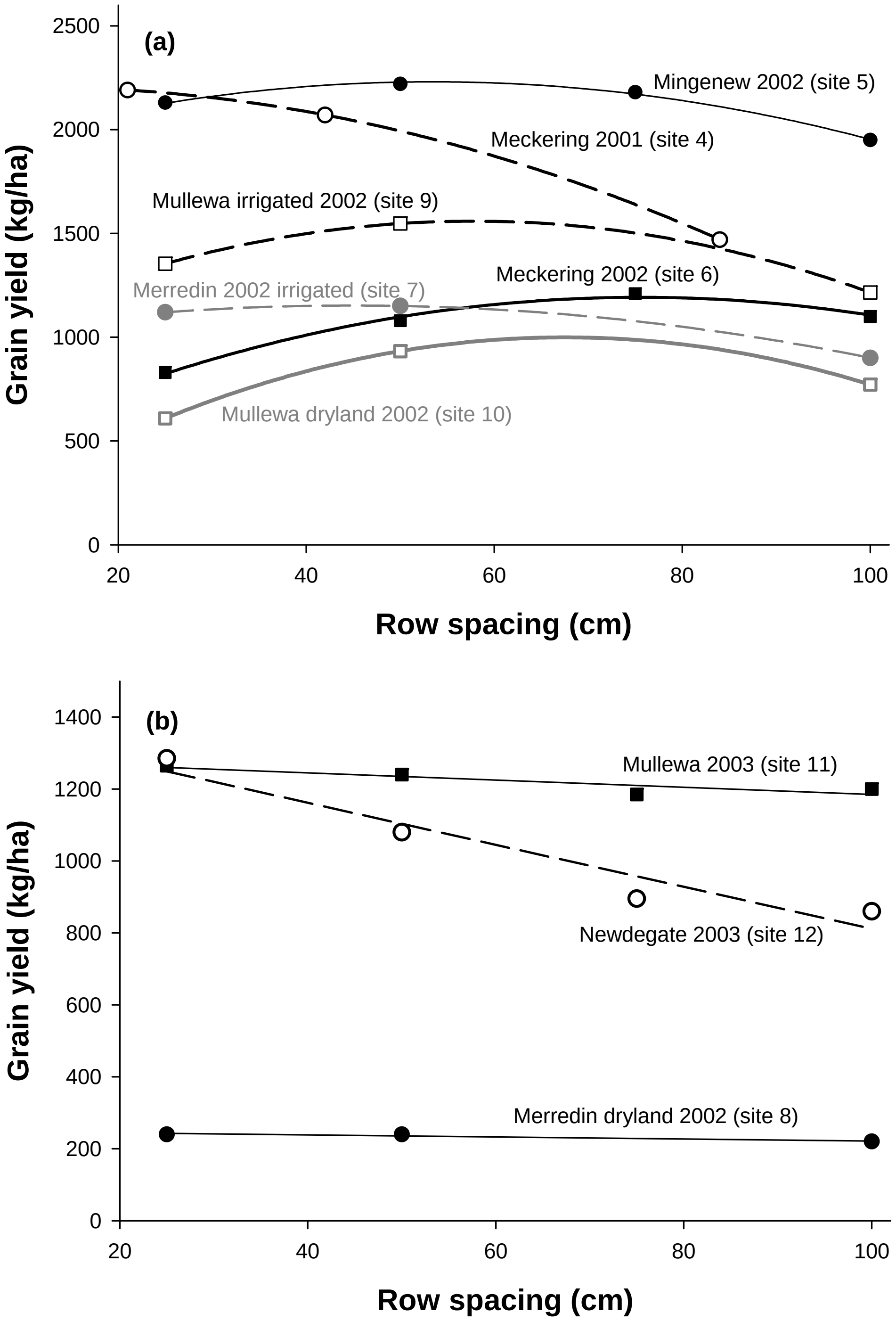

Figure 17 Responses in yield by narrow-leaf lupins (Lupinus angustifolius) in WA to changes in row spacing where the response appeared either quadratic (a) or near linear (b)(see Appendix 5 for site details).

A two-phase linear approach addressed this non linearity by limiting the range of row spacing to more closely approximate linearity. Data were initially limited to 18 cm to 30 cm minimum, and 42 cm to 60 maximum row spacings (Figure 18a). These data were compared with the data previously presented for wheat and canola for WA (Figure 18a). Lupin yield frequently increased with row spacings above 18 cm up to about 50 cm. This increase reduced slightly with increased $Yield_{18}$. This result contrasted with that of wheat and canola in WA and showed lupins, when grown in that State, were better adapted to wider row spacings. Data from NSW were added to Figure 18a (red numbers), and indicated that lupin yields in NSW generally decreased as rows spacing widened, but there was too much variability in the data to fit a linear function.

When rows were widened beyond 42-50 cm to 84-100 cm (Figure 18b) there appeared to be a yield loss. The rate of loss of yield of lupins in WA was similar to that of wheat and canola for data from WA (Figure 18b). With the other crops reviewed in this monograph the relationship between yield and row spacing was linear throughout the range of row spacings evaluated, although data was limited. In 12 of 89 experiments on wheat there was a maximum row space of ≥50 cm. Only five experiments had a maximum row space of 75 cm or more. Three of 18 experiments with barley had row spacing of 50 cm or more, and 11 of 33 experiments with canola exceeded 50 cm row spacing (Appendices 1, 3 and 4).

It was unclear as to why lupins in WA were so different from other crops, and lupins in NSW, in their response to row space widening. While lupins and canola are both dicotyledons and of indeterminate flowering, lupins were the only legume crop studied. Their placement in cropping rotations would be following a cereal crop in situations of depleted N fertility. This low N fertility may be particularly exacerbated on the sandy soils in WA. The particular observation that lupins in the northern wheatbelt of WA were at an advantage, or at least not disadvantaged, when sown in wide rows up to about 50 cm (Harries and French 2007) places the lupin crop in an environment of light textured soils and potentially drier spring conditions, where wheat was low yielding and sometimes advantaged by wide row sowing (Blackwell *et al.* 2006). How these factors may interplay is not understood.

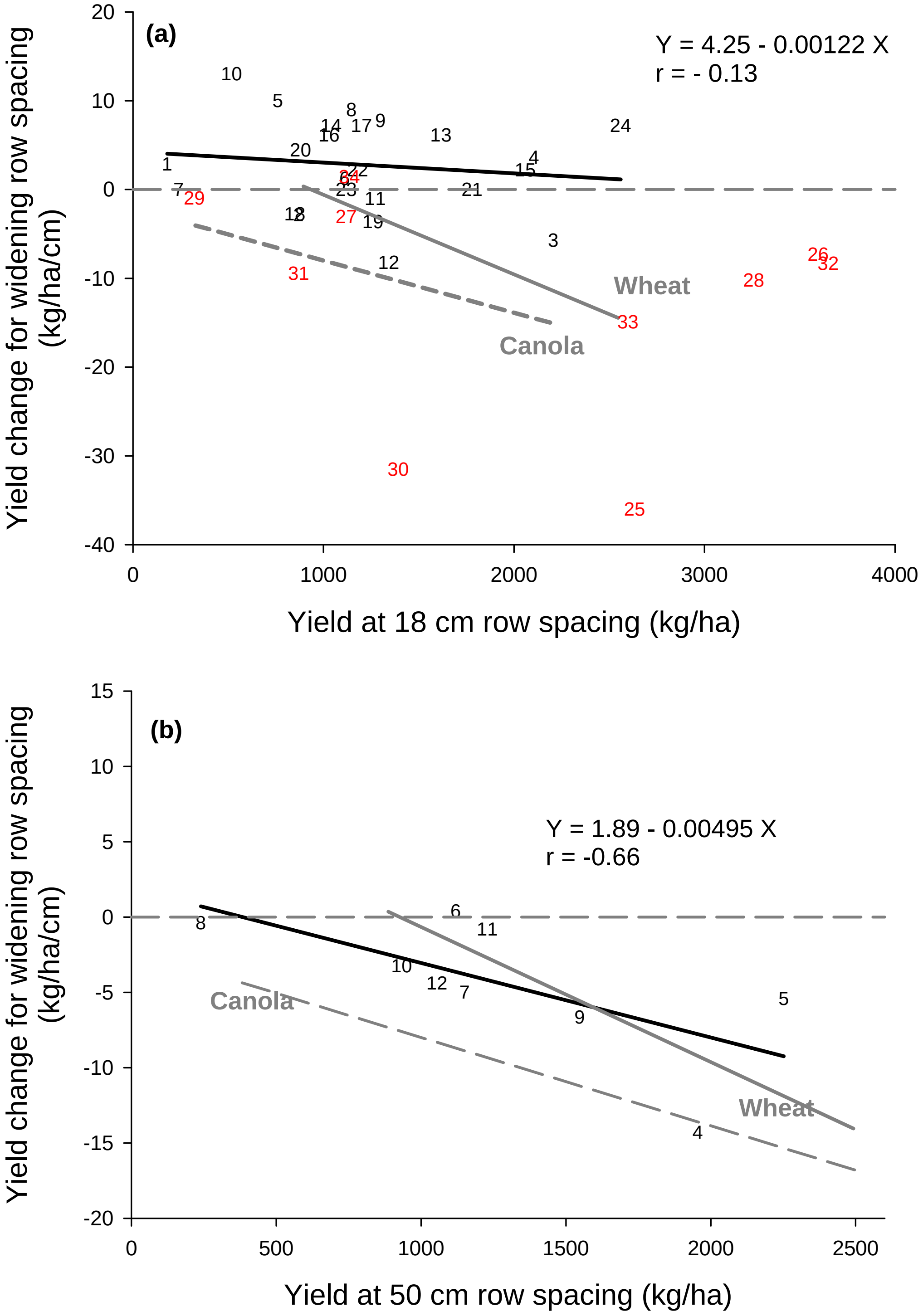

Figure 18 Relationship between yield and the rate of yield loss for lupins in WA when (a) data were limited to 18 cm to 30 cm minimum, and 42 cm to 60 cm maximum and fitted to give yield loss in relation to yield at 18 cm rows (NSW data in red; wheat and canola lines for WA are shown in the same graph in grey), and (b) data was limited to 42 cm to 50 cm minimum and 84 cm to 100 cm maximum fitted to give yield loss in relation to yield at 50 cm rows (wheat and canola lines for WA in the same graph in grey).

5. Agronomy, row spacing and yield

A number of studies have examined changes in agronomic practices and their effects on yield loss with widening of row spacing. In the monograph to this point any agronomic practices that seem realistic have been averaged. This section examines claims of agronomic practice modifying yield loss from wide row spacings.

5.1 Limiting loss of yield with wide rows by changed 'in-crop' agronomy

It is implicit in Figure 8 that any agronomic practice lowering $Yield_{18}$ is likely to also lower the rate of yield loss with increased row spacing (kg/ha/cm of row space widening). In these studies it was necessary to also relate yield loss to the $Yield_{18}$ values as some practices may achieve a lowering of yield loss by simply reducing $Yield_{18}$.

This was demonstrated in the research of Fettell and Bamforth (1986). These authors examined the interaction of row spacing (with wheat at 15 cm, 25 cm and 35 cm at Condobolin NSW) both with and without competition from annual ryegrass. The data presented in Table 10 has been modelled (linear fitted) to estimate yield at both 18 cm and 36 cm row spacing with the different agronomic practices, so the yield loss can be assessed with a knowledge of $Yield_{18}$.

In the research of Fettell and Bamforth (1986) yield loss was always less with the wider row spacings in weedy crops (even a yield increase in experiment three) compared with the weed free crops. However, growing weedy crops with wide row spacing was not advantageous as weed free crops were higher yielding than weedy crops at 36 cm row spacing. This result demonstrated that agronomic practices that lower $Yield_{18}$ can commonly reduce yield loss from the widening of row spacing. Weedy crops had less loss of yield from row space widening than weed free crops, but they also had lower yields at both 18 cm and 36 cm row spacings.

Table 10 Yield and yield loss estimates for wheat in weed free and weedy crops in three experiments at Condobolin NSW (derived from Fettell and Bamforth 1986).

Experiment	Practice	Yield at 18 cm (kg/ha)	Yield at 36 cm (kg/ha)	Yield loss (kg/ha)
1	Weed free	3010	2540	470
	Weedy	2520	2110	410
2	Weed free	2130	1920	210
	Weedy	1600	1520	80
3	Weed free	1230	1200	30
	Weedy	840	1010	-170

Other agronomic practices that lower the yield loss with widening of rows may be observed to lower $Yield_{18}$. The interactions between row spacing and cultivars, nitrogen application rate, time of sowing and spread of seed within the row have been studied in WA (Amjad and Anderson 2006). These data have been fitted to linear relationships. $Yield_{18}$, yield at 36 cm row spacing and yield loss are presented in Table 11.

Within small tolerances, the agronomic practice that gave highest yield at 18 cm rows also gave highest yield at 36 cm row spacing, with only one exception. The suggestion then was that $Yield_{18}$ has a dominant influence on yield as rows widen to 36 cm, and that differences in the rate of loss of yield between practices were smaller in their effect.

Table 11 Yield and yield loss estimates for wheat at two row spacings comparing a number of agronomic practices in WA (derived from Amjad and Anderson 2006).

Site	Practice	Yield at 18 cm (kg/ha)	Yield at 36 cm (kg/ha)	Yield loss (kg/ha)
Salmon Gums 2000	**N rate**			
	46 kg/ha N	1670	1590	80
	23 kg/ha N	1690	1330	360
Lort River 2001	**Time of sowing**			
	May	2640	2430	210
	June	2070	1590	480
Salmon Gums 2001	**Time of sowing**			
	May	2830	2410	420
	June	2400	2170	230
Salmon Gums 2002	**Seed spread in sowing row**			
	25 mm	1100	870	230
	50 mm	990	990	0
	75 mm	990	990	0

The exception to this generalisation was that a narrow spread of seed within the row (25 mm width) gave highest yield at 18 cm rows and lower yield at 36 cm rows.

Retaining stubble on the soil surface, compared with burning stubble, removing or incorporating stubble, has been suggested as a likely advantage for crop yield as row space widens (Scott *et al.* 2010). A stubble mulch is assumed to protect the soil surface in the inter-row space and minimise evaporation of moisture from the soil. This hypothesis was tested using data mainly from WA (Riethmuller pers comm.) with some experiments from NSW (Doyle and Felton 1984; Fettell and Bamforth 1986). Stubble removal was through burning, except for Doyle and Felton (1984) where stubble was incorporated by cultivation. The relationships between $Yield_{18}$ and rate of yield loss with increased row spacing were fitted independently for the retained surface stubble, and the burnt or cultivated stubble treatments (Figure 19). This approach permitted a comparison of stubble retained and burnt treatments against a background of tillage treatments, which independently influenced grain yield (Riethmuller 2004b).

The relationships did not vary significantly, indicating stubble retention has no direct advantage over stubble burning or incorporation as row space increases. The WA data fitted this statement well with no difference between relationships with and without stubble (data not presented). However, the NSW data tended to have stubble retained treatments showing less yield loss than where stubble was removed.

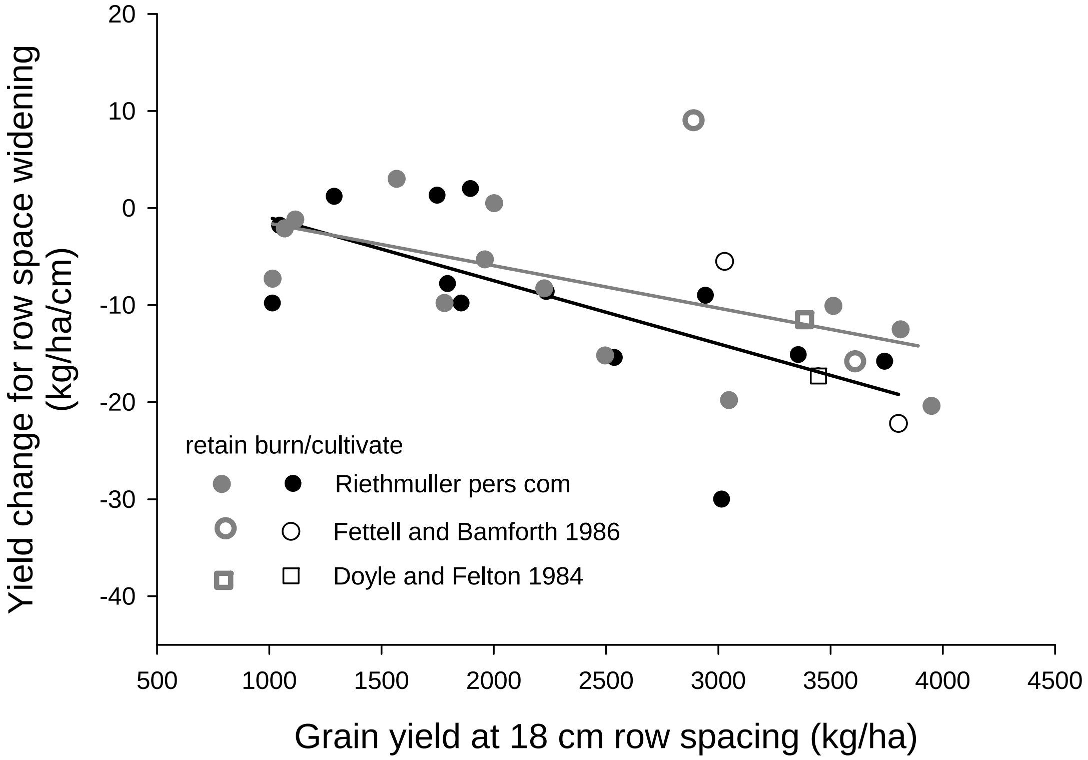

Figure 19 The relationships between the yield of wheat with 18 cm row spacing and the rate of loss of yield with row widening, for retained surface stubble (grey points and fitted line) and burnt or incorporated stubble (black points and fitted line).

Numerous experiments have investigated the interaction between row spacing and sowing rate. In this monograph the research of Fawcett (1964, 1967) and Auld *et al.* (1983) has already been described. This research indicated a lower rate of yield loss in wheat with row space widening as plant populations increased to about 200 wheat plants/m^2. The corollary to this was that increased sowing rates may prevent or minimise yield loss where row spacing was widened.

Data for wheat in Australia indicated this was generally not the case (Table 12). Six experiments showed no significant interaction between row spacing and sowing rate or resultant plant population (Doyle 1980; Yunusa *et al.* 1993). A further five experiments, likely to have had significant interactions, had an interaction which did not support the notion that higher sowing rates of wheat gave a lower rate of yield loss with row widening (Newman and Weeks 2000; Amjad and Anderson 2003; Blackwell *et al.* 2006). Where yield responded to increased sowing rate the response was in narrow rather than wide rows. Only two experiments supported the suggestion that higher sowing rates reduce yield loss when widening row spacing (Giles *et al.* 2006).

Re-examining the research of Fawcett (1964, 1967), Figure 6b and c shows that increased rectangularity (row spacing) reduced yield at densities of about 200 plants/m^2. Increased plant density reduced, but did not eliminate, the loss of yield from widening rows. Only in Figure 6a (Auld *et al.* 1983; Kemp *et al.* 1983) does a density of 200 plants/m^2 eliminate yield loss with increased rectangularity.

At sowing rates near optimal for a given environment, increases in sowing rate are likely to have a small or negligible effect in reducing yield losses incurred by widening row spacings.

Table 12 Some studies on row spacing and sowing rate with wheat in Australia.

Reference	Row spacing (cm)	Sowing rate/plant population	Comment
Doyle (1980)	18, 27, 36	22, 33, 44 kg/ha	No interaction in five seasons at Tamworth, NSW
Yunusa *et al* (1993)	9, 18, 27	85, 147 plants/m^2	No interaction in one season at Merredin, WA
Doyle and Felton (1984)	12.5, 25, 37.5, 50, 70	20, 40 kg/ha	'Wheat grain yield was increased by raising the seeding rate…difference increased as row spacing decreased.' Single site, Tamworth, NSW.
Amjad and Anderson (2003)	18, 24, 30	50, 100, 150, 200, 250 plant/m^2	'Higher seeding rates…only increased yields at the narrowest row spacing…. On average, higher seeding rates had no beneficial impact, or reduced yield, at the wider row spacing.' Gibson and Salmon Gums, WA
Newman and Weeks (2000)	18, 36	30, 60, 90, 120 kg/ha	Significant response in grain yield to sowing rate at 18 cm row spacing, but not at 36 cm. Mingenew, WA
Blackwell *et al* (2006)	30, 60	30, 60 kg/ha	Larger increase in yield to increased row spacing at 60 kg/ha than at 30 kg/ha, but maximum yield at 60 cm and 30 kg/ha.
Giles *et al* (2006)	18, 36	40, 80 kg/ha	Rates of yield loss less with increased row spacing at 80 kg/ha than at 40 kg/ha. Mean data from two experiments in SA

5.2 Wide row spacing and altered sowing systems

Paired rows

'Paired row' or 'ribbon row' (i.e. wide seed and fertiliser spread) sowing appears to offer some scope in mitigating the loss of grain yield as row space is widened. However, the practices simply reduce the space between seed rows, while maintaining the specified gap between sowing tines (Figure 20).

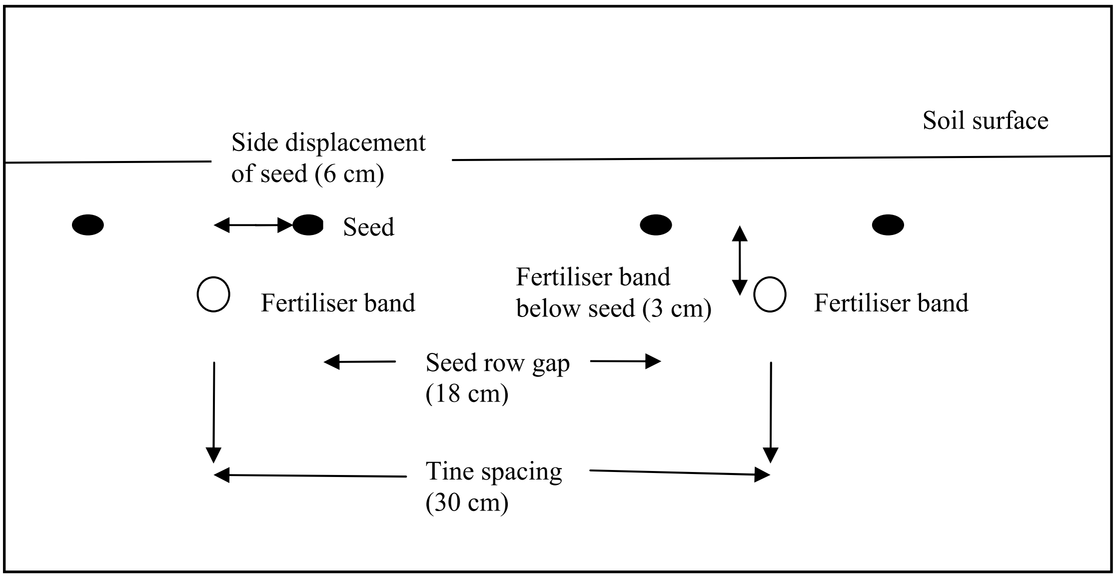

Figure 20 A vertical section through a paired row sowing arrangement showing the tine spacing and vertical and horizontal displacement of seed and fertilisers bands. Measurements given are for Mead and Newell (undated)(see text below).

Mead and Newell (undated) at Cowra NSW used a system where a single fertiliser band was placed 3 cm below the dual seed rows, with the seed rows also displaced 6 cm to either side of the fertiliser band. Sowing at 30 cm row spacing (tines at 30 cm centres) resulted in the seed rows being 12 cm apart across the fertiliser band, and only 18 cm apart in the gap between fertiliser bands (Figure 20).

Xie *et al.* (1998) in Canada had an unspecified displacement of the fertiliser band below the seed depth, and a side displacement of the seed rows from the fertiliser band of 3.3 cm. Sowing with a tine spacing of 30 cm using this system would give a gap in the seed rows over the fertiliser band of only about 7 cm, and a gap between fertiliser rows of about 23 cm. Both these arrangements have the seed rows closer together than the tine spacing while maintaining early access of the seedlings to the fertiliser band.

As row space increased, the paired row sowing system maintained higher grain yields in both wheat and canola in Manitoba, Canada (Xie *et al.* 1998; canola data not presented) and Cowra, NSW (Mead and Newell undated)(Table 13 and 14). This statement was not always correct, as effects in wheat were slight in the 1995 season in Manitoba (Table 13), and faba beans showed little effect at Cowra (data not shown).

The effect was in part ascribed to the improved emergence density of the crops in paired rows (Xie *et al.* 1998; Mead and Newell undated). This was presumably a result of reduced plant competition due to the halving of plant density per metre of row in the paired row system. In both paired and single row sowing the fertiliser band was separated from the seed band (Xie *et al.* 1998; Mead and Newell undated).

Paired row sowing appears to offer some advantage, but there has been little research in Australia (see also Long *et al.* 2002; Evans 2003). Paired row sowing is a variation of the wide spread of seed and fertiliser in the sown row (Amjad and Anderson 2006), and both cause increased soil disturbance compared with either no-till sowing (<20% soil disturbance) or zero-till sowing (<5% soil disturbance). The combination of paired row sowing with inter-row sowing could be somewhat self defeating if the tine space needs to be further widened to permit the use of paired rows.

Table 13 Wheat yield (kg/ha) and plant emergence (plants/m^2) at various row spacings for a single row and a paired row system in wheat in Canada (after Xie et al. 1998).

Row	Row	1993		1994		1995	
spacing	system	Yield	Emergence	Yield	Emergence	Yield	Emergence
25 cm	Single	2160	251	2290	291	2630	179
	Paired	2750	254	2800	334	2630	203
38 cm	Single	1990	189	2180	246	2600	198
	Paired	2680	240	2700	334	2470	219
51 cm	Single	730	78	na	na	na	na
	Paired	1690	164	na	na	na	na

na not available

Table 14 Wheat and canola yield (kg/ha) in 1999 season and emergence density of wheat(plants/m^2) in 2000 season at Cowra NSW (after Mead and Newell undated).

Row spacing (cm)	Row system	Wheat		Canola
		Yield in 1999 (kg/ha)	Emergence in 2000 (plant/m^2)	yield in 1999 (kg/ha)
18	Single	4980	129	2100
	Paired	na	na	na
36	Single	4630	108	1900
	Paired	5600	145	2010
54	Single	3780	98	1970
	Paired	4400	110	2020
72	Single	4030	74	1890
	Paired	4270	89	2000

na not available

Inter-row sowing

The adoption of inter-row sowing in southern and central NSW is a recent innovation. The system is similar to earlier wide-row sowing except the stubble between wide rows is standing stubble, where in previous systems of stubble retention it was either incorporated, slashed or simply sown through, and so the arrangement of stubble was variable. The arrangement of rows of newly-sown crop rows between rows of the previous year's standing stubble present some unique issues.

The physical separation of the new seedlings from the old crowns of the previous crop can inhibit the infections of crown rot caused by the fungus *Fusarium pseudograminearum* , and common root rot caused by *Bipolaris sorokiniana* (Simpfendorfer *et al.* 2004; Simpfendorfer *et al.* 2006). The authors suggest the value of inter-row sowing is that it reduces the rate of inoculum build-up in a paddock. However, it is not a comprehensive answer, but a useful component of an integrated disease management system.

The presence of standing stubble between the rows of a newly sown crop could potentially limit the efficacy of herbicides. Foliar or soil-applied herbicides could strike the standing stubble, which would interfere with the spray's ability to contact weeds or the soil surface. A portion of the herbicide could lodge in the stubble and then leach or volatilise from the stubble (Banks and Robinson 1982; Petersen and Shea 1985; Dao 1991; Wolf *et al.* 2000). The effects of standing stubble in the inter-row of the new crop, rather than continuous standing stubble or flattened stubble are unclear. The machinery blocking effect of stubble in the inter-row of crop on weed control by cultivation has been noted (Riethmuller *et al.* 2007).

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

Wide rows (17.5 cm versus 35 cm) with mulched stubbles have been shown to increase infection by bean yellow mosaic virus (Jones 1994). Conversely, the spread of cucumber mosaic virus in lupins can be inhibited with wider row spacing with no stubble present (Bwye *et al.* 1999). The effect of standing stubble in the inter-row is unclear. The open canopy in wide row sowings with higher wind speed and lower humidity has been claimed to provide a less disease prone environment than in crops with narrow row spacing (Peltzer *et al.* 2009). Again the presence of standing stubble in the inter-row of crops could be expected to negate the 'open crop' effect.

This monograph has already covered the problems of plant nutrition with inter-row sowing. The residual fertiliser band from a previous crop is located remotely from the new crop placement, limiting the contribution of residual fertiliser to crop nutrition. With fertiliser banded in widely spaced rows it is difficult to achieve representative sampling before sowing the second crop. The questions remains as to whether the soil sample should be random, presumably to include the previous fertiliser band, or taken only in the stubble inter-row space; the site of planting the new crop.

5.3 Genotype of crop and reaction to wider rows

There appears to have been no active breeding for adaptation to wide row spacing. However a range of studies has investigated tillering capacity, crop height and the leaf inclination as possible adaptations suited to wider row spacing. These characteristics have been proposed as likely to give higher groundcover and light interception, and so suppress weed growth and enhance yield under wider row conditions.

Johnson *et al.* (1988) evaluated five cultivars of wheat for their reaction to row spacing (10 cm and 20 cm) in south eastern USA across two seasons. In this high-yielding environment (average grain yield of 5000 kg/ha; with a range of 3900-6300 kg/ha) there was no significant interaction between cultivar and row spacing, suggesting that cultivars all reacted similarly to changes in row spacing.

Marshall and Ohm (1987) evaluated 16 genotypes of wheat for their reaction to row spacing (6.4 cm and 19.2 cm) across two seasons in Indiana, USA. The narrower row spacing produced a higher grain yield across both seasons (6480 kg/ha versus 6070 kg/ha during 1983, and 4220 kg/ha versus 4010 kg/ha during 1984). While the authors identified significant genotype by row space interactions these frequently varied between seasons and only one cultivar (cv Benni) gave a consistent, significant loss of yield with the widening of rows.

Drews *et al.* (2009) working in Germany, studied three row spacings (12 cm, 17 cm and 24 cm), and three cultivars of wheat that differed in shading ability. Their interest was in cultivar competitiveness with weeds in an organic farming situation. They reported that cv Pegassos was most competitive (tall with planophile leaves) compared with cv Greif and wide rows permitted greater accumulation of weed biomass. In only one experiment of six was there a cultivar/row spacing interaction in groundcover at the start of stem extension. Cultivars Greif and Astron had higher groundcover at 12 cm compared with 24 cm row spacing, while groundcover Pegassos was only slightly affected by row spacing at this growth stage. Grain yields were not reported in this paper.

In Australia row spacing and cultivar interactions have been studied in WA (Amjad and Anderson 2003, 2006). Grain yield was fitted to a linear model and the grain yield at 18 cm and 36 cm row spacing has been estimated from the model (Table 15). The highest-yielding cultivar at the 18 cm row spacing was also the highest yielding cultivar at 36 cm row spacing. In other words the main effect of cultivar was the greater effect when compared with cultivar by row spacing interaction.

Table 15 The effect of cultivar of wheat on the grain yield at increased row spacing in WA in three seasons (derived from Amjad and Anderson 2006).

Site	Cultivar	Yield at 18 cm (kg/ha)	Yield at 36 cm (kg/ha)	Yield loss (kg/ha)
Salmon Gums 2000				
	Camm	1680	1460	210
	Cascade	1330	1120	210
	Westonia	1810	1510	290
Lort River 2001				
	Camm	2210	1890	320
	Cascade	2430	2010	420
	Westonia	2430	2140	290
Salmon Gums 2001				
	Camm	2500	2260	240
	Cascade	2660	2270	390
	Westonia	2690	2340	350

There was also an interaction between row spacing and cultivar in canola for one season (2007), but not in another (2008; Kleemann and Gill 2010a). In 2007 the cultivar Hyola 50 appeared to maintain yield with wider row spacings. This row space by cultivar interaction in grain yield appeared to be due to the lower yield of Hyola 50 at 18 row spacing, rather than to any superior yield at 36 cm or 54 cm row spacings (Table 16). Carlton (2004) carried out five experiments in WA where row space (20 cm and 40 cm), and two cultivars of canola were compared in factorial combination with three sowing rates. There was no significant interaction between row space and cultivar at any site.

Table 16 The yield (kg/ha) of canola cultivars at Roseworthy, SA in response to increased row spacing in 2007 (from Kleemann and Gill 2010a), reprinted with permission[5]*.*

	Row spacing (cm)		
Cultivar	18	36	54
		Yield (kg/ha)	
AV-Garnet	1490	1560	1240
Tarcoola	1750	1290	1240
Hyola 50	1130	1230	1270
Hyola 75	1370	1420	1100
LSD (P = 0.05) for row space x cultivar		297	

The only clear evidence of genotype differences likely to have a bearing on row spacing were presented by Fischer *et al.* (2005). Working on raised beds gave uneven spacing. The two rows on the bed were separated by 20 cm and the gap between beds gave a row spacing of 55 cm (20 cm, 55 cm arrangement). With three rows on the bed, the configuration was 18 cm, 18 cm, 44 cm. Experiments across two years compared yield under this three-row-per-bed arrangement with even 20 cm, 20 cm row spacing on a flat seed bed and indicated the cultivars released by CIMMYT after the late 1980s coped better with the 44 cm gap than earlier cultivars.

In summary, there was some evidence that cultivars could differ in their response to wide row spacing. However, while interactions between row spacing and genotype have been recorded, these interactions can be misleading or were not reproducible across seasons. The highest yields at wide rows were usually associated with the cultivar with the highest yield at 18 cm rows. Alternatively the advantage in yield at 18 cm rows disappeared at wider row spacing.

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[5] © Australian Agronomy Society (2010), 8 May, 2013.

6. General discussion and conclusions

The major driver of interest in wide row spacings is the need to sow through stubble in no-till and retained stubble systems. Further interest relates to compatibility of sowing rows and machinery in the northern NSW and Queensland systems that produce both summer and winter crops, and to the improved yield of lupins at wide row sowings in WA.

From the point of view of adopting conservation farming, the widening of rows is an 'enabling' change, which makes sowing through stubble achievable. The benefits of wide row spacings in stubble handling have been greatest when high stubble loads are present. However this would be more frequent in higher rainfall areas where higher grain yields are common, and this is where reductions in grain yield from wide rows are likely to be greatest.

The losses in grain yield from wide row sowing have been estimated using long term data from Wagga Wagga (high rainfall wheatbelt NSW), Condobolin (low rainfall NSW) and Merredin (low rainfall WA; Table 17). Estimates for Wagga have been based on a long term rotation experiment where wheat yields were available for 27 years (1979-2005; MK Conyers pers comm; see Heenan *et al.* 2004). This experiment was sown with 18 cm rows and the data used was the average yield of the stubble burnt, stubble retained, conventional tillage and no-till treatments in lupin-wheat rotations. The experiment was phased and wheat yield was available for each year. The relationship in Figure 8 was used to estimate yields at 30 cm and 36 cm. The Condobolin experiment had 21 years of data (1979-1999) on continuous wheat with tillage and stubble burn/retain treatments (NA Fettell, unpublished; see Fettell and Gill 1995). As this experiment was sown at 21 cm rows, yield at 18 cm, 30 cm and 36 cm rows was estimated based on the relationship in Figure 8. Merredin data covered 13 years in which row spacing data were available for wheat within the period 1987-2006 (Riethmuller pers comm; see Riethmuller 2004a). The data on yield at various row spacings (9 cm, 18 cm, 27 cm and 36 cm) were used to estimate the yield of wheat at 18, 30 and 36 cm row spacings using linear regression for each year, and the effect of row widening estimated from that relationship (Table 17).

Table 17 Estimates of grain yield and changes of yield (kg/ha) from row space widening beyond 18 cm for three sites based on annually recorded wheat yields.

	Site		
	Wagga Wagga	Condobolin	Merredin
	Average yield (kg/ha)		
18 cm row spacing	3440	1840	2230
[range 18 cm yields]	[370-6760]	[0[a]-3850]	[1020-3850]
30 cm row spacing	3240	1750	2130
36 cm row spacing	3140	1710	2070
	Average yield change from row widening (kg/ha)		
30 cm row spacing	-200	-90	-110
[range 30 cm change]	[+30 to -440]	[+10 to -230]	[+30 to -300]
36 cm row spacing	-300	-130	-160
[range 36 cm change]	[+40 to -670]	[+20 to -340]	[+40 to -450]

[a] not harvested in three years due to drought

Average yield losses due to using wider rows were estimated, but could vary considerably with season conditions. Yield gains were small compared with higher yielding seasons where losses were more substantial. However, this seasonal variability seemed to have a relatively small effect when estimating long term yield loss from row space widening. Using the general relationship between yield and row space yield loss (Figure 8) and the average yields at the three sites, the loss of yield at Wagga Wagga, NSW for row spacings of 30 cm and 36 cm would be 200 kg/ha and 300 kg/ha, which were the same values in Table 17. Similarly, for Condobolin, NSW the values were 80 kg/ha and 120 kg/ha compared with 90 kg/ha and 130 kg/ha in Table 17. For Merredin, WA losses were 110 kg/ha and 170 kg/ha, compared with 110 kg/ha and 160 kg/ha when variability of yield with season was considered (Table 17). Despite considerable variability of yield changes with row widening due to changes of yield with seasonal conditions long term effects can be reasonably estimated from long term average yield and the relationship in Figure 8.

While the loss of yield is a detrimental effect of wider rows, farmers need to compare this impact with any associated cost savings or yield advantages. The major factors to consider include: fuel savings of fewer tines or discs on a seeder, and/or the savings accrued from a smaller tractor to match a seeder with fewer tines. Sowing speed also has been claimed to lead to earlier sowing on average and yield advantages are likely to be derived from that earlier sowing.

Benefits of earlier sowing resulting from faster sowing can be approximated. At Wagga Wagga, NSW delayed sowing reduced grain yield by 3.7% for each week of delay after the end of April (Kohn and Storrier 1970). This can be compared with average yield loss given in Table 17. Assuming a 15-day sowing operation using 18 cm rows with slow ground speed, then this sowing operation would take 10 days at 36 cm row spacing at a ground speed of 1.5 times the original speed. The 'average' date of sowing would be 2.5 days earlier using wide rows if there was a continuous sowing operation. The wide row sowing would have a yield gain of 1.3% ([2.5/7]*3.7%) due to earlier sowing, but yield loss of 8.7% ([300/3440)*100]; Table 17) due to wide row sowing. Where sowing was not continuous, the duration of delay would be seasonally dependent. On a farm-wide basis sowing would need to average 2.4 weeks earlier to fully counter the negative impact on yield of row widening. At Wagga Wagga, NSW, with favourable sowing conditions, the effects could be expected to be smaller than in low rainfall areas where seasonal 'breaks' can be more variable.

Fuel savings associated with changing row spacing of tines from 25 cm to 50 cm have been estimated to range from 0.54 litres/ha to 1.84 l/ha of diesel, depending on soil type and sowing point (Jones and O'Halloran 2006).

The yield losses from wide row sowing presented in this monograph were generally larger than reported in other regional reviews. The percentage yield losses from widening rows from 18 cm to 36 cm was 8.7% on average at Wagga Wagga NSW (average yield 3440 kg/ha, yield loss 300 kg/ha; Table 17), 7.1% at Condobolin and 7.2 % at Merredin. Smith *et al.* (1995) in SA summarised the yield loss from widening row spacing from 18 cm to >30 cm was 4.3%, when most studies had wide rows at 36 cm. In WA, Leonard (1993) suggested that 4% of grain yield was lost with the row spacing changing from 18 cm to 36 cm. Additionally, as reported in this monograph, WA and SA may have a more rapid loss of yield with row widening than other states. As expected, the appraisal of yield loss at Merredin, WA (7.2% at 36 cm row spacing) agreed with the estimate of 7 % (Riethmuller 2004b) and was based on the same data set.

This evidence supports Smith *et al*. (1995) that when approaching the issue of stubble handling and passage of machinery, that row widening should be the last option to be adopted. Other more favourable options include; tine and frame height, shank shape, rank placement and disc seeders. If farmers adopt wide rows, the most promising approach is likely to be to use paired rows with the wide tine spacings. Paired rows would have the likely benefit of increased competition with weeds

The conclusion for wheat, barley and canola was that narrow row spacings were associated with higher grain yield, except in situations of low yield for wheat and barley. This general loss of yield with wider rows also applies to other crops. Whish *et al.* (2005) concluded that with sorghum in eastern Australia, yield potential was highest with solid row sowing (100 cm row space), while skip row systems (equivalent of 'wide rows') limited yield potential, but made achieving an acceptable yield in a low yield situation more reliable. Lyon *et al.*(2009) reached a similar conclusion when researching row pattern for maize. Solid planting (every row at 760 cm) was superior at sites yielding an average of 3400 kg/ha, and at lower yielding sites (average 1100 kg/ha) skip row patterns yielded the most.

The scope for overcoming the yield penalties of wide row sowing of wheat by agronomic means or appropriate cultivar choice seem limited. The most appropriate action seems to be sound agronomy and cultivar selection aimed at maximising grain yield. In the reviewed data, this approach generally gave highest yield irrespective of row spacing in the reported experiment.

7. Appendices

Appendix 1 Some data on the 89 experiments on wheat used to produce Figure 8.

Site	State /region	Locality	Year	Row spacing (cm)	Comment	Reference
1	Central NSW	Condobolin	1984	15, 25, 35	Exp 1 (averaged over weed ^{2})	Fettell and Bamforth (1986)
2	Central NSW	Condobolin	1984	15, 25, 35	Exp 2 (averaged over weed ^{2})	“
3	Central NSW	Condobolin	1984	15, 25, 35	Exp 3 (averaged over weed ^{2})	“
4	Central NSW	Condobolin	1985	18, 24, 31	Exp 4 dryland (averaged st burnt dd & cc)	“
5	Central NSW	Condobolin	1985	18, 24, 31	Exp 4 irrigated (averaged st burnt dd & cc)	“
6	SA	Turretfield	1985	18, 36		Smith *et al.* (1995)
7	SA	Tanunda	1986	12, 18, 27, 36		“
8	SA	Arthurton	1986	12, 18, 27, 36		“
9	SA	Tanunda	1987	12, 18, 27, 36		“
10	SA	Arthurton	1987	12, 18, 27, 36		“
11	SA	Merilden	1988	9, 18, 35	Averaged across 3 sowing rates	“
12	SA	Mintaro	1989	9, 18, 35	Averaged across 3 sowing rates	“
13	SA	Clare	1988	9, 18	Averaged across 3 sowing rates	“
14	SA	Clare	1989	9, 18	Averaged across 3 sowing rates	“
15	SA	Clare	1989	9, 18	Averaged across 3 sowing rates	“
16	SA	Wokurna	1992	18, 31		“
17	SA	Wokurna	1993	18, 31		“
18	Central NSW	Cowra	2007	15, 30		Martin *et al.* (2009) Edwards and Martin (2007)
19	Central NSW	Cowra	2008	18, 36		Martin *et al.* (2009)
20	Sth NSW	Jerilderie	2008	15, 30		“
21	Sth NSW	Merriwagga	2008	22, 45		“
22	Sth NSW	Yanco	2008	18, 24, 36	Dryland	“
23	Sth NSW	Yanco	2008	18, 24, 36	Irrigated	“
24	Sth NSW	Narrandera	1985	18, 20, 30, 35		Hill (1988)
25	Sth NSW	Narrandera	1986	18, 20, 30, 35		“
26	Sth NSW	Narrandera	1987	18, 20, 30, 35		“
27	Sth NSW	Merriwagga	1985	18, 20, 30, 35		“
28	Sth NSW	Moombooldool	1986	18, 20, 30, 35		“
29	Sth NSW	Moombooldool	1987	18, 20, 30, 35		“
30	Sth NSW	Balranald	1985	18, 20, 30, 35		“
31	Sth NSW	Balranald	1986	18, 20, 30, 35		“
32	Nth NSW	Tamworth	1974	18, 27, 36	Averaged across 3 sowing rates	Doyle (1980)
33	Nth NSW	Tamworth	1975	18, 27, 36	Averaged across 3 sowing rates	“
34	Nth NSW	Tamworth	1975	18, 27, 36	Averaged across 3 sowing rates	“
35	Nth NSW	Tamworth	1977	18, 27, 36	Averaged across 3 sowing rates	“
36	Nth NSW	Tamworth	1978	18, 27, 36	Averaged across 3 sowing rates	“
37	Nth NSW	Tamworth	1983	12.5, 25, 37.5, 50, 75	Tilled trts; averaged over sowing rates	Doyle and Felton (1984)
38	WA	Merredin	1989	9, 18, 27	Collgar sandy loam; meaned over sowing rates	Yunusa *et al.* (1993)
39	WA	Merredin	1989	9, 18, 27	Merredin sandy loam	“
40	WA	Gibson	2000	18, 24, 36	Site 1; main effect of row spacing	Amjad and Anderson (2006)
41	WA	Salmon Gums	2000	18, 24, 36	Site 2; main effect of row spacing	“
42	WA	Lort River	2001	18, 24, 36	Site 3; main effect of row spacing	“
43	WA	Salmon Gums	2001	18, 24, 36	Site 4; main effect of row spacing	“
44	WA	Salmon Gums	2002	18, 24, 36	Site 5; main effect of row spacing	“
45	Central NSW	Cowra	1999	18, 36, 54, 71		Mead and Newell (undated)
46	Nth NSW	Narrabri	1961	18, 36	Experiment 1-1 at 44 kg/ha sowing rate	Fawcett (1967)
47	Nth NSW	Narrabri	1961	18, 36	Experiment 1-5 at 44 kg/ha sowing rate	“
48	Nth NSW	Narrabri	1962	18, 36, 53, 74, 89	Experiment 5 at 44 kg/ha sowing rate	“
49	Nth NSW	Narrabri	1963	10, 14, 19, 28, 38	Experiment 4 at 44 kg/ha sowing rate	“

50	Victoria	Dooen	1980	18, 22, 30, 36		Ridge (1981)
51	Nth NSW	Liverpool Plains	2000	17.5, 35, 52.5	Average 120 and 150 plants/m^2	Butler *et al.* (2003)
52	Nth NSW	Liverpool Plains	2001	17.5, 35, 52.5	Average 120 and 180 plants/m^2	“
53	WA	West Moora	2004	22, 66	60 kg/ha seed with highest fertiliser input	Bowden *et al.* (2005)
54	Sth NSW	Burumbuttock	2009	18, 24, 36		P Martin unpublished
55	Central NSW	Cowra	2009	18, 24, 36		P Martin unpublished
56	Sth NSW	Deniliquin	2009	18, 24, 36	Irrigated	Smith and Martin (2011)
57	Sth NSW	Wagga Wagga	2009	18, 24, 36		P Martin unpublished
58	Sth NSW	Merriwagga	2009	25,50, 75		B Haskins unpublished
59	Victoria	Mininera	2007	20, 30	Averaged across 3 cultivars and 2 N timings	Wardle and Steele (2008)
60	WA	Merredin	1987	9, 18, 27, 36	Averaged across stubble burnt and retained (cultivated)	Riethmuller (2004b and pers comm)
61	WA	Merredin	1988	9, 18, 27, 36	Averaged across stubble burnt and retained (cultivated)	“
62	WA	Merredin	1989	9, 18, 27, 36	Averaged across stubble burnt and retained (cultivated)	“
63	WA	Merredin	1990	9, 18, 27, 36	Averaged across stubble burnt and retained (cultivated)	“
64	WA	Merredin	1991	9, 18, 27, 36	Averaged across stubble burnt and retained (cultivated)	“
65	WA	Merredin	1993	9, 18, 27, 36	Averaged across stubble burnt and retained (cultivated)	“
66	WA	Merredin	1995	9, 18, 27, 36	Averaged across stubble burnt and retained (no till)	“
67	WA	Merredin	1997	9, 18, 27, 36	Averaged across stubble burnt and retained (no till)	“
68	WA	Merredin	1998	9, 18, 27, 36	Averaged across stubble burnt and retained (no till)	“
69	WA	Merredin	2001	9, 18, 27, 36	Averaged across stubble burnt and retained (no till)	“
70	WA	Merredin	2003	9, 18, 27, 36	Averaged across stubble burnt and retained (no till)	“
71	WA	Merredin	2004	9, 18, 27, 36	Averaged across stubble burnt and retained (no till)	“
72	WA	Merredin	2006	9, 18, 27, 36	Averaged across stubble burnt and retained (no till)	“
73	SA	Roseworthy	2006	18, 36, 54		Kleemann and Gill (2010b)
74	SA	Roseworthy	2007	18, 36, 54		“
75	SA	Roseworthy	2008	18, 36, 54		“
76	SA	Roseworthy	2004	17.5, 35	Averaged across 2 cultivars	Giles *et al.* (2006)
77	SA	Roseworthy	2005	17.5, 35	Averaged acrossr 2 cultivars	“
78	WA	Carnamah	1999	18, 36	Average of 90 and 120 kg/ha sowing rates	Newman and Weeks (2000)
79	Sth NSW	Yanco	2010	18, 24, 36	Irrigated	P Martin unpublished
80	Sth NSW	Burrumbuttock	2010	18, 24, 36		P Martin unpublished
81	Central NSW	Cowra	2010	18, 24, 36		P Martin unpublished
82	Sth NSW	Deniliquin	2010	18, 24, 36		Smith and Martin (2011)
83	Sth NSW	Wagga Wagga	2010	18, 24, 36		P Martin unpublished
84	Sth NSW	Merriwagga	2010	25, 50, 75		B Haskins unpublished
85	Sth NSW	Wagga Wagga	2008	18, 36		P Martin unpublished
86	Sth NSW	Wagga Wagga	2006	15, 30		P Martin unpublished
87	Central NSW	Cowra	2007	18, 36		P Martin unpublished
88	Sth NSW	Wagga Wagga	2011	18, 24, 36		P Martin unpublished
89	Sth NSW	Merriwagga	2011	25, 50, 75		B Haskins unpublished

Appendix 2 Some data on the 17 experiments on wheat from the USA used to produce Figure 11.

Site	State /region	Locality	Year	Row spacing (cm)	Comment	Reference
1	Montana	Mocassin	2004	15, 30	Averaged across sowing and N rates	Chen *et al.*(2008a)
2		“	2005	15, 30	“	"
3	Pennsylvania	Lancaster County	1981	12.7, 17.8	Averaged across sowing rates, sowing depths and spring N	Frederick and Marshall (1985)
4		“	1981	12.7, 17.8	“	"
5		“	1981	12.7, 17.8	“	"
6		Centre County	1981	12.7, 17.8	“	"
7		“	1981	12.7, 17.8	“	“
8		Lancaster County	1982	12.7, 17.8	“	“
9		“	1982	12.7, 17.8	“	“
10		Centre County	1982	12.7, 17.8	“	“
11	Georgia	Plains	1985 & 86	10, 20	288 plants/m^2; averaged across 5 cultivars	Johnson *et al.* (1988)
12		“	“	10, 20	576 plants/m^2; averaged across 5 cultivars	“
13	Virginia	Coastal Plain	1981	10, 20	Suffolk sandy loam; averaged across 3 sowing rates	Joseph *et al.* (1985)
14		“	1981	10, 20	Pactolous loamy sand; averaged across 3 sowing rates	“
15		“	1982	10, 20	State sandy loam; averaged across 3 sowinging rates	“
16	Indiana	West Lafayette	1982	6.4, 19.2	Averaged across 2 sowing rates and 16 cultivars	Marshall and Ohm (1987)
17		“	1983	6.4, 19.2	“	"

Appendix 3 Some data on the 18 Australian experiments on barley used to produce Figure 14.

Site	State /region	Locality	Year	Row spacing (cm)	Comment	Reference
1	WA	Cascade	2005	24, 48	Averaged across 4 cultivars	Paynter and Hills (2007)
2	WA	Gibson	2005	24, 48	“	Paynter and Hills (2007); (Paynter 2010)
3	WA	Katanning	2005	18, 36	“	
4	WA	Meckering	2005	18, 36	“	
5	WA	Mt Madden	2005	25, 50	“	
6	SA	Roseworthy	2006	18, 36, 54		Kleemann and Gill (2008)
7	Central NSW	Parkes	2007	17, 24, 30, 38	Averaged across 4cultivars, and till and no-till	Fettell (2008)
8	“	Condobolin	2007	17, 24, 30, 38	“	
9	Sth NSW	Temora	2008	17, 24, 30, 38	Averaged across cultivars	Fettell (2009)
10	Central NSW	Parkes	2008	17, 24, 30, 38	“	
11	“	Condobolin	2008	17, 24, 30, 38	“	
12	“	Condobolin	2008	17, 30, 43	“	
13	“	Condobolin	2008	17, 30, 43	“	
14	“	Rankin Springs	2008	22, 44, 66	“	
15	WA	Merredin	2007	9, 18, 27, 36		Riethmuller *et al.* (2008a)
16	Victoria	Manangatang	2007	15, 22.5, 30	Averaged across 10 cultivars	Moody and Best (2008)
17	“	Birchip	2007	15, 22.5, 30	Averaged across 10 cultivars	
18	“	Longerenong	2007	15, 22.5, 30	Averaged across 6 cultivars	

Appendix 4 Some data on the 33 experiments on canola from the Australia used to produce Figure 16.

Site	State /region	Locality	Year	Row spacing (cm)	Comment	Reference
1	Sth NSW	Merriwagga	2007	15, 60	Averaged across 5cultivars	Haskins (2008) Martin *et al.* (2011)
2	WA	North Tenindewa	1997	22.5, 35	Averaged across deep banding and drilled fertiliser	Sandison and Lee (1998)
3	WA	Merredin	1999	9, 18, 27, 36	Averaged across stubble management treatments	Riethmuller pers com
4	WA	Merredin	2009	9, 18, 27, 36	“	Riethmuller pers com from Walton G unpub
5	WA	Mt Barker	1994	18, 36	94MT12	Riethmuller pers com
6	WA	Wongan Hills	1994	18, 36	94WH11	“
7	WA	Frankland	1995	18, 36	95MT77	Walton (1996)
8	WA	Gairdner River	1995	18, 36	95MT75	Walton (1996)
9	WA	Esperance Downs	1995	18, 36	95ES129	Walton (1996)
10	WA	Avondale	2002	18, 36	02NO37	Riethmuller pers com Pathan *et al.*(2005; 2006)
11	WA	West Moora	2004	22, 66	Sowing rate 6 kg/ha	Bowden *et al.* (2005)
12	Nth NSW	Tamworth	2001	32, 64	'Weed free' treatment	Felton *et al.* (2004)
13	Nth NSW	Tamworth	2002	32, 64	'Weed free' treatment	“
14	Nth NSW	Tamworth	2003	32, 64	'Weed free' treatment	“
15	Central NSW	Cowra	2007	18, 36		Martin *et al.* (2011)
16	Sth NSW	Burrumbuttock	2008	18, 36		“
17	Central NSW	Cowra	2008	18, 36		“
18	SA	Roseworthy	2007	18, 36, 54	Averaged across 4 cultivars	Kleemann and Gill (2010a)
19	SA	Roseworthy	2008	18, 36, 54	Averaged across 4 cultivars	“
20	SA	Mintaro	2003	23, 45, 68	Averaged across 2 cultivars	Anon (2004)
21	Central NSW	Merriwagga	2010	25, 50, 75		Martin *et al.* (2011)
22	Sth NSW	Wagga Wagga	2010	18, 24, 36		“
23	Central NSW	Cowra	2009	18, 24, 36		“
24	Central NSW	Condobolin	2008	21, 42, 63		“
25	Sth NSW	Junee	2009	18, 22, 30		McCaffery *et al.* (2010)
26	Sth NSW	Junee	2008	18, 22, 30		McCaffery *et al.* (2009)
27	Sth NSW	Cootamundra	2010	18, 22, 30	Averaged across 2 cultivars	McCaffery (2011)
28	WA	Dalwallinu	2003	20, 40	cv Stubby; averaged across 3 sowing rates	Carlton (2004)
29	WA	Kellerberrin	2003	20, 40	“	“
30	WA	Hyden	2003	20, 40	“	“
31	WA	Tincurrin	2003	20, 40	“	“
32	Sth NSW	Merriwagga	2011	25, 50, 75	Averaged across 5 cultivars	P Martin unpublished
33	Sth NSW	Wagga Wagga	2011	18, 24, 36	“	“

Appendix 5 Some data on the 24 experiments on lupins from Western Australia and 10 experiments in NSW used to produce Figure 18.

Site	State /region	Locality	Year	Row spacing (cm)	Comment	Reference
1	WA	Chapman Valley	1995	17.5, 35	CMV infection in seed; Exp 5	Bwye *et al.* (1999)
2	WA	Badgingarra	1995	17.5, 35	CMV infection in seed; Exp 6	"
3	WA	Mullewa	2001	30, 60	Main effect; some confounding with tramlines and spraying	Blackwell and Collins (2002)
4	WA	Meckering	2001	21, 42, 84	Trial 1	Crabtree *et al.* (2002)
5	WA	Mingenew	2002	25, 50, 75, 100	Averaged across 2 sowing rates and 2 sowing times	Fosbery *et al.* (2003)
6	WA	Meckering	2002	25, 50, 75, 100	"	"
7	WA	Merredin	2002	25, 50, 100	Irrigated	French and Wahlsten (2003)
8	WA	Merredin	2002	25, 50, 100	Dryland	"
9	WA	Mullewa	2002	25, 50, 100	Average across 2 cultivars; irrigated (100 mm pre sowing)	Harries *et al.* (2003)
10	WA	Mullewa	2002	25, 50, 100	Average across 2 cultivars; dryland	"
11	WA	Mullewa	2003	25, 50, 75, 100	Averaged across 2 sowing times	Harries and French (2007)
12	WA	Newdegate	2003	25, 50, 75, 100	Averaged across 2 sowing times	"
13	WA	East Nabawa	1991	18, 36		Jarvis (1992)
14	WA	Badgingarra	1991	18, 36		"
15	WA	Badgingarra	1991	18, 36		"
16	WA	Wongan Hills	1991	18, 36		"
17	WA	East Brookton	1991	18, 36		"
18	WA	Merredin	1991	18, 36		"
19	WA	Carabin	1991	18, 36	Average across stubble burnt and stubble retained	"
20	WA	Belka	1991	18, 36		"
21	WA	Belka	1991	18, 36		"
22	WA	Varley	1991	18, 36		"
23	WA	Varley	1991	18, 36		"
24	WA	Gibson	1991	18, 36		"
25	NSW	Merriwagga	2010	25, 50, 75		P Martin unpublished
26	NSW	Wagga	2010	18, 24, 36		"
27	NSW	Wagga	2009	18, 24, 36		"
28	NSW	Cowra	2008	18, 36		"
29	NSW	Merriwagga	2007	15, 60		"
30	NSW	Cowra	2007	15, 30		"
31	NSW	Wagga	1995	18, 36		D Lemerle unpublished
32	NSW	Wagga	1999	18, 36		D Lemerle unpublished
33	NSW	Merriwagga	2011	25, 50, 75		P Martin unpublished
34	NSW	Wagga	2011	18, 24, 36		"

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