CSIRO PUBLISHING
www.publish.csiro.au/journals/cp

Review
Crop & Pasture Science, 2009, **60**, 395–406

Weed management in wide-row cropping systems: a review of current practices and risks for Australian farming systems

S. C. Peltzer[A,I], *A. Hashem*[B], *V. A. Osten*[C], *M. L. Gupta*[D], *A. J. Diggle*[E], *G. P. Riethmuller*[F], *A. Douglas*[G], *J. M. Moore*[A], *and E. A. Koetz*[H]

[A]Department of Agriculture and Food Western Australia, 444 Albany Highway, Albany, WA 6330, Australia.
[B]Department of Agriculture and Food Western Australia, PO Box 484, Northam, WA 6401, Australia.
[C]Department of Primary Industries and Fisheries, LMB 6 Emerald, Qld 4720, Australia.
[D]School of Land, Crop and Food Sciences, University of Queensland, Gatton, Qld 4343, Australia.
[E]Department of Agriculture and Food Western Australia, Locked Bag 4, Bentley Delivery Centre, WA 6983, Australia.
[F]Dryland Institute, Department of Agriculture and Food Western Australia, Great Eastern Highway, Merredin, WA 6415, Australia.
[G]Department of Agriculture and Food Western Australia, 10 Dore St, Katanning, WA 6317, Australia.
[H]EH Graham Centre, NSW DPI, Pine Gully Road, Wagga Wagga, NSW 2650, Australia.
[I]Corresponding author. Email: speltzer@agric.wa.gov.au

Abstract. Growing agricultural crops in wide row spacings has been widely adopted to conserve water, to control pests and diseases, and to minimise problems associated with sowing into stubble. The development of herbicide resistance combined with the advent of precision agriculture has resulted in a further reason for wide row spacings to be adopted: weed control. Increased row spacing enables two different methods of weed control to be implemented with non-selective chemical and physical control methods utilised in the wide inter-row zone, with or without selective chemicals used on the on-row only. However, continual application of herbicides and tillage on the inter-row zone brings risks of herbicide resistance, species shifts and/or changes in species dominance, crop damage, increased costs, yield losses, and more expensive weed management technology.

Introduction

More than 3500 years ago, the Chinese invented the seed drill that planted directly into rows in the ground rather than throwing seed onto the fields at random. The first multi-row seeder was developed by Jethro Tull (1731); it could sow three rows simultaneously. Since then, a plethora of machinery has been designed that will sow crops in a variety of row spacings as well as at a variety of depths, through stubble, and incorporate fertiliser at the same time. The accepted traditional row spacing is 7 inches (or 18 cm) for autumn-sown winter cereals in Australia (Anderson and Garlinge 2000), based on the early mechanical seeders. As row spacings increased, they became multiples of 7 inches and became referred to as ‘wide’. Very wide row spacings of 112 cm traditionally allowed for the width of a horse to be able to till between the rows (Wicks *et al*. 1995). Summer cereals are traditionally grown in 90 cm rows.

When sowing crops in rows, the spacing between must be chosen to maximise both yield and profit. In an ideal world, the perfect row spacing is where the spacing between the plants along the row equals the distance between the rows (Fischer and Miles 1973). As the row spacing increases and the crop sowing rate remains the same, and as there are more plants within the row, rectangularity increases. Plants that are equidistant from their neighbours should do better than plants bunched together in widely spaced rows due to reduced inter-species competition, maximum light interception, and less evaporation of water from the soil surface (Anderson and Garlinge 2000). Growing crops at wider than optimum row spacings is obviously a consequence of less than ideal conditions.

The extent to which row spacings may be widened without reduction in yield depends on the sowing rate and plant population within the row. As the row spacing increases and the plant population increases within the row, crop yield will remain the same until a yield plateau is reached (Puckridge and Donald 1967). At that plateau, tillering or flowering per plant may be reduced but the production of seed may remain the same. At excessively high plant numbers within the row, however, the yield declines due to reduced seedling emergence and increased disease, etc. (Donald 1963; Anderson and Garlinge 2000). The optimal crop sowing rate should give rise to the optimal plant population for maximum yield and profit.

The ability of a particular crop to withstand increases in row spacing while maintaining sowing rate depends on crop species. There is negligible yield penalty when crops such as narrow-leafed lupins (*Lupinus angustifolius* L.) are grown in 50- or 74-cm-wide row spacings compared with the traditional 25 cm

10.1071/CP08130 1836-0947/09/050395

(French 2004). Doubling the row spacing from 32 to 64 cm did not reduce the yields of chickpea (*Cicer arietinum* L.), faba bean (*Vicia faba* L.), or canola (*Brassica napus* L.) under weed-free conditions (Felton *et al*. 2004; Harries *et al*. 2005). There was also no yield penalty in chickpeas after the row spacing was increased to 75 cm, although yields did decrease at high sowing rates of up to 80 kg/ha (Felton *et al*. 1996). Similarly, increasing the row spacing from 25 to 100 cm did not reduce the yield of narrow-leafed lupin at 50 kg/ha sowing rate in the northern agricultural region of Western Australia (Harries *et al*. 2005). There were yield reductions, however, when the sowing rate was increased to 150 kg/ha (Harries *et al*. 2005) and they were grown in wetter areas or at very late sowing times (French 2004). In another Western Australian study, canola was found to be sensitive to a row spacing increase from 23 to 36 cm, with a yield reduction of 17.5% (Sandison and Lee 1998). For northern Australian summer crops, there is also little difference in yields of sunflower (*Helianthus annuus* L.) with row spacings of 36–100 cm in both dryland and irrigated crops. In northern New South Wales and southern Queensland, the most common row spacing of sunflower is 75 cm because it suits planters using 37.5 cm row spacing for winter crops (Belfield *et al*. 2006). But in the dry subtropics, row spacing has a marked effect on sunflower yields, with reductions of 25–30% when moving from 50 to 100 cm rows with moderate crop populations of 35 000 plants/ha (Osten *et al*. 2006). A similar trend has been recorded in sorghum grown at 60 000 plants/ha across Queensland, with yields reduced by 20–40%t as rows widened from 1 m solid to single (third row missing) and double-skip (third and fourth row missing) (Osten *et al*. 2006). In Western Australia, the row spacing for wheat is usually ~18 cm in burnt stubble systems. Increasing the row spacing from 18 to 54 cm decreased the yield by an average of 8% for every 9 cm increase (Anderson and Garlinge 2000). Similarly, wheat (*Triticum aestivum* L.) was sensitive to an increased row spacing from 32 to 64 cm, reducing the yield in 2 out of 3 years in New South Wales (Felton *et al*. 1996). In stubble retention systems, the yield decrease may even be higher due to difficulty in achieving optimal crop establishment at the wider row spacings.

The optimal plant population varies with management practices and site variables such as climate, soil type, water, weeds, and diseases (Donald 1963; Anderson and Barclay 1991). For example, the optimal number of cotton plants under irrigated conditions in Queensland is 8–12 plants/m of row compared with 5–8 for dryland cotton (Harris 1999). The recommended plant densities for desi chickpea vary across locations, with 50 plants/m^2 recommended for most crops in south-western Australia compared with 40 plants/m^2 in subtropical southern Queensland (Beech and Leach 1989; Jettner *et al*. 1999). Where plant growth is limited by dry conditions or delayed sowing, there is little inter-plant competition and crops sown at a high density are able to produce more seed (Donald 1963). This tends to push the recommended sowing density up with late seasons.

Increased row spacing can be used to manipulate soil moisture, preserving water in the drier regions by delaying the development of water stress during reproductive growth and deferring the use of water stored between rows (French and Wahlsten 2003). In Australia, summer crops such as sorghum (*Sorghum bicolour* L. Moench), sunflower, cotton (*Gossypium hirsutum* L.), chickpea, and soybean (*Glycine max* L.) may be grown in rows wider than 1 m or in skip-row configuration where every third (single-skip) or third and fourth (double-skip) rows are not planted.

Wider row spacings have become common as conservation tillage becomes more widely adopted and crops are grown with minimal disturbance of the soil. In a recent survey of natural resource management on Australian farms, 70% of farmers had adopted direct drill and minimum tillage practices (Hodges and Goesch 2006). Site-specific management problems, such as pests, diseases, and frost incidence, may also force the rows to be widened, especially in conservation tillage systems.

Another reason for increasing row spacing is to facilitate a novel method to control herbicide-resistant weeds. As the number of weed species with herbicide resistance and the extent of their spread increases, the chemical options available for weed control become more limited. In Australia, herbicide labels display a letter denoting the mode of action of the active ingredient and, in Western Australia in 2005, annual ryegrass (*Lolium rigidum* Gaud.) had developed resistance to 9 major herbicide mode-of-action (MOA) groups. Western Australian researchers estimated that nearly 90% of all populations had plants with resistance to MOA Group B sulfonylurea herbicides. Similarly, wild radish (*Raphanus raphanistrum* L.) had developed resistance to herbicide MOA groups B, C, F, and I, and the number of populations is increasing rapidly (Walsh *et al*. 2007). The use of precision agriculture combined with increased row spacings allows distinct ‘on-row’ and ‘inter-row’ zones to be defined, enabling two different methods of weed control to be implemented. Non-selective chemical and physical control methods can be used in the wide inter-row zone, reducing the reliance on selective herbicides. On the row, there is scope to use more expensive selective herbicides to which weeds have not developed resistance. The area sprayed with these chemicals is greatly reduced when used in the on-row zone rather than as a traditional blanket spray, potentially reducing the risk of herbicide resistance development.

Although wide row spacing for weed management opens up some alternatives to control herbicide-resistant weeds, there are also disadvantages associated with this new system. These include risks associated with the increase in row spacing such as decreased yields, reduced competition with weeds (Fischer and Miles 1973), and problems with rotations. Continual pressure by non-selective herbicides, such as glyphosate and mixtures of paraquat and diquat (Spray.Seed®), in the inter-row, along with the timing of the inter-row herbicide application or tillage, may lead to further herbicide resistance and weed species composition shifts. There may also be economic risks and herbicide registration issues.

This paper describes cropping in wide row spacings in the southern winter cropping areas of Australia as well as both winter and summer cropping in the northern parts. This would also apply to broadacre dryland cropping in the Mediterranean and subtropical regions of the world. It describes increasing row spacings for the novel two-zone weed control system and discusses the risks associated with it as well as the more conventional reasons for increasing row spacing such as water conservation, stubble handling, and crop management.

Conventional reasons for wide row spacings

Widening crop rows is a tool to enable rationing of critical resources, particularly water. Crops grown on wide row spacing have greater intra-row resource competition, while the resources in the inter-row are preserved. However, the availability of water depends on the capacity of the soil to store it and the amount and timing of replenishment, with the latter component subject to seasonal variability (Whish *et al*. 2005). Wide rows essentially ensure some temporal and spatial water availability in water-limiting crop environments, thus minimising the risk of water deficits at critical crop growth stages to ensure profitable yields (Whish *et al*. 2005; Collins *et al*. 2006). In addition, winter cereals and chickpea may be sown in wide rows to improve moisture-seeking abilities of the sowing operation; for example, chickpea may be sown as deep as 15 cm, requiring the majority of soil above the seed to be displaced to the sides and creating an obvious furrow (Reid *et al*. 2004). Wide row systems may also leave some water in the profile post-harvest, providing opportunities for double cropping, particularly in regions that can move from summer into winter crops and where chances of in-crop winter rain are diminished (Whish *et al*. 2005).

Presence of weeds will have a major effect on water availability to crops irrespective of planting geometries. Hence good weed management becomes critical to the success of wide row systems, as failure to control water-using weeds defeats the purpose of wide row cropping where water conservation is the focus.

Stubble (standing or surface crop residues) retention is a common practice in conservation cropping systems. Despite many benefits such as moisture and nutrient conservation, soil erosion control, and improved soil health and structure (Laflen *et al*. 1978; Allmaras and Dowdy 1985; Freebairn *et al*. 1993; Carter 1994), it also presents problems at the time of sowing, which can be minimised by sowing the crop in wider row spacings (Siemens and Wilkins 2006).

Generally, the sowing operation is easier in wide row spacings than in narrow spacings in no-till systems. Increasing tine spacings to sow crops in wider rows allows greater amounts and lengths of crop residues to pass through them, which minimises the blockage commonly encountered in narrow row spacings (Lafond 1994; Amjad *et al*. 1996; Slattery 1998). Wider rows also facilitate the use of row clearing attachments, which help to maintain uniform sowing depth, resulting in good and uniform plant emergence.

The adoption of wide row seeding can also be done to expand the management options available to farmers. Changes in row spacings may increase the risk of disease and pest incidence and severity or may enhance control due to differences in canopy closure, humidity, and other factors (Jones 1994; Bwye *et al*. 1999). For example, an increase in row spacing may increase the number of bean yellow mosaic virus (BYMV)-carrying aphids landing on bare ground, resulting in an increased infection of the crop due to the delay in canopy closure (Jones 1994). Similarly, Septoria development in wheat is greater in narrow row spacings (Tompkins *et al*. 1993). Wide rows had greater wind speeds while narrow row plots had increased duration of leaf wetness, cooler air, and higher relative humidity.

Increased row spacing for weed management

Another reason for increasing row spacings is for weed management. This is particularly pertinent in recent times where traditional broadcast application of herbicides is not suitable because of herbicide resistance. Widening the row spacings allows the definition of on-row and inter-row zones where completely different methods of weed control can be used, such as selective chemicals in the on-row zone and non-selective chemical, physical, or mechanical methods in the inter-row zone. The selective chemicals used in the on-row zone may otherwise be too expensive to use across the paddock.

Inter-row chemical control and shielded spray herbicide application

In recent years there has been a rapid increase in the use of shielded spraying equipment, which is designed to go between wide rows of crop to allow the use of knockdown herbicides on the inter-row weeds and selective herbicides on the on-row.

The major herbicide used between the rows is glyphosate, but there is scope for the use of tank mixes of alternative herbicides (Burgis 2002; Hashem *et al*. 2005) and combinations of herbicide applications such as double knockdown, which is a full rate of glyphosate followed with a full rate of paraquat products. Within the row, due to the reduction in area sprayed, there is potential to use expensive selective herbicides or residual banded herbicides at sowing (Crabtree *et al*. 2002). Inter-row spraying of non-selective herbicides with spray-shield in a lupin crop sown at 75 cm did not result in grain yield reduction at the grower level at Cunderdin, WA (Maling *et al*. 2007).

Tillage and mechanical weed control

Mechanical destruction of weeds is an ancient technology and, after the introduction of herbicides, reliance and research into innovative mechanical weed control technologies decreased. With the advent of herbicide resistance, however, chemical methods of weed control can become less effective and mechanical methods are becoming more competitive relative to herbicides (Mohler *et al*. 1997).

The selectivity of mechanical inter-row weed control depends on the crop species as well as the type of tillage implement, time of tillage, relative growth of crop to weed, speed of operation, and weather conditions after the operation (Melander *et al*. 2003; Melander 2006). Lupins are well suited to inter-row disturbance (Jensen *et al*. 2004) as they are a stiff-stemmed crop, with current cultivars producing little if any yield from the lower basal branches (Harries 2005; Harries *et al*. 2005), and are therefore quite tolerant of being covered by soil (Kouwenhoven 1997). Plant stand losses due to inter-row cultivation disturbances were 39–55% in narrow-leafed lupins (Hashem *et al*. 2008), depending on the timing and method of tillage.

Under high weed densities, cultivation is often less effective in controlling weeds and maintaining crop yields than inter-row spraying (Amador-Ramirez *et al*. 2001). Inter-row cultivation treatments in narrow-leafed lupins in Western Australia were not successful in controlling high densities of annual ryegrass of

5000 plants/m^2 (Collins and Roche 2002). Inter-row cultivation may also stimulate weed germination and thus reduce the efficacy of control (Peltzer and Matson 2002; Peltzer *et al*. 2007).

There are a few physical methods to selectively target weeds within a row, such as brush weeders and hoes (Kouwenhoven 1997). Ridging or throwing soil onto the row as the inter-row tillage is reported as one possible method (Baumann and Slembrouck 1994). However, ridging by soil throw is only successful in smothering small weeds and the selectivity depends on the relative growth difference between weeds and crop.

Tillage can be used in combination with herbicides (Baumann and Slembrouck 1994; Mohler *et al*. 1997). The use of residual pre-emergent herbicides such as triazine, pendimethalin, trifluralin, and metribuzin to suppress weeds allowed a longer time between emergence and the requirement for mechanical weed control, resulting in reduced crop damage (Amador-Ramirez *et al*. 2001). Use of atrazine and pendimethalin banded on the crop row in combination with cultivation resulted in weed cover and grain yields equivalent to a broadcast herbicide alone (Mt. Pleasant *et al*. 1994). A combination of on-row banded herbicide together with inter-row tillage gave a 40% yield increase over broadcast spraying of herbicide in barley on 40 cm rows (Abu-Hamdeh 2003).

Alternative methods

Inter-row mowing followed by herbicide application has been shown to be effective. In Western Australia, Hashem *et al*. (2005) mowed between rows of narrow-leafed lupins at York in 2003 and applied Spray.Seed® after mowing. This resulted in control of 75% of inter-row annual ryegrass plants, giving a 13% yield increase over an untreated control plot. In a similar experiment targeting wild radish, glyphosate and Spray.Seed® application after mowing gave 87–89% control, respectively. In the US, Donald *et al*. (2001) found that inter-row mowing of weeds, without herbicide application, very close to the soil surface 2 or 3 times, killed or suppressed summer annual grasses and broad-leafed weeds when timed properly. Inter-row mowing also controlled weeds and yielded as well as or better than broadcast applied herbicide at the same rates.

Flame weeders that kill weeds through direct contact with a flame were tested against conventional herbicide application, shielded sprayer, weed wipers, and cultivation biomass (Collins and Roche 2002). Inter-row flaming gave the poorest control of annual ryegrass, measured as fresh weed. Hot water weed control has also been tested for inclusion in organic agricultural circumstances (Hansson and Ascard 2002). This is impractical due to high energy usage, logistics, and the number of applications required for adequate control.

Issues and risks for weed management

Competition with weeds in wide row spacings

Competition between crop plants and weeds occurs when the supply of a common resource such as space, nutrients, water, and light is below the combined demand (Donald 1963). The extent of the competition depends on how far apart the plants are, and is inversely proportional to the square of the distance apart. The increased row spacing associated with wide row cropping decreases the competitive effect of the crop on the weeds within the inter-row. Given the constant density, the number of crop plants within the row (or intra-row) increases as the row space becomes wider. This higher intra-row crop density also means greater inter-specific competition with weeds on the rows (Wells 1993). An increased on-row crop density may also increase crop *v*. crop competition and reduce yield if an appropriate crop sowing rate is not set under wide row spacing (Felton *et al*. 1996, 2004).

Decreasing crop plant population and increasing row spacing decreases crop competitive ability against weeds, and generally wider row spacing will reduce crop competition for homogeneously distributed production factors, as postulated mathematically (Fischer and Miles 1973). Annual ryegrass seed-head production was increased by over 90% when the wheat row spacing was increased from 90 to 270 mm and the seeding rate was reduced from 400 to 50 kg/ha in Western Australia (Minkey *et al*. 1999). After 18 years of an experiment with row spacings of 90, 180, 270, and 360 mm and stubble retained or burnt, increasing row spacing increased annual ryegrass seed-set by an average of 1.9% for each millimetre increase in row spacing from 90 mm (Riethmuller 2004). The competitiveness of wide-row sorghum in southern Queensland was similarly shown to be reduced as the row spacing was widened, resulting in increased weed growth and seed production (Osten *et al*. 2006).

The extent of the crop's competitiveness depends on early vigour and the natural competitive characteristics of crop plants, which according to Pester *et al*. (1999) include rapid emergence and root development, increased height, canopy closure, high leaf area index, profuse tillering or branching, and allelopathy. Time to canopy closure is an inverse function of row spacing and plant population. Conservation farming often reduces crop competitive ability due to poor establishment, reduced early vigour, and wider crop row spacing (Jordan 1993; Mohler 1993; Minkey *et al*. 1999; Lemerle *et al*. 2001; Olsen *et al*. 2005).

Since crops and weeds compete for nutrients, the placement and timing of fertiliser application can affect the competitive balance, particularly when the crop rows are widely spaced. Strategic fertiliser placement ensures that the nutrients are more likely to be used by the crop rather than by weeds, giving the crop a competitive advantage (Cochran *et al*. 1990; Melander *et al*. 2003; Blackshaw and Molnar 2004; Blackshaw *et al*. 2005). Due to the differences in nutrient requirements of the crops and the weed species, the timing of nutrient application may also be important (Forcella 1984; Lemerle *et al*. 2001), although often the effect is less than the effect of placement (Blackshaw and Molnar 2004).

Weed emergence and timing of weed control

An alteration in crop row spacing will have little effect on the time of emergence and the early growth stages of weeds, only on the magnitude of competition experienced by the crop. The weeds that emerge before or with the crop will have a higher competitive impact than weeds emerging after the crop (Hock *et al*. 2006). When 10 weed species were seeded into a soybean crop in the US and grown into row spacings of 19 or 76 cm apart, the later-emerging weeds were smaller and had less effect on soybean yield than those emerging earlier. The effect of row spacing was greater on earlier than on later emerging weeds. This was likely due to canopy closure, which may affect the late emergence of weeds by reducing light intensity and changing soil temperature and other climatic conditions (Egley 1986) and the eventual growth and development of both crop and weeds (Knezevic *et al*. 2003).

Although the inter-row weeds are removed by non-selective treatments in wide row systems, the timing of weed control is important. If it is too early, some weed cohorts may avoid control and emerge to compete with the crop (Hilgenfeld *et al*. 2004*a*) and set seed at the end of the season. The critical time for weed removal and yield maximisation can vary with row spacing (Mulugeta and Boerboom 2000; Knezevic *et al*. 2003). In the US, where similar densities of weeds were present in soybean on three different row spacings, the critical time for weed removal was delayed substantially by reduced row spacings: 6 days after emergence (DAE) in 76 cm rows compared with 21 DAE in 19 cm rows (Knezevic *et al*. 2003). This was due to less vigorous weed growth in the narrower rows. The practical implication of this is that planting soybean in wide rows (76 cm) reduces early-season crop tolerance to weeds and so weed management needs to be implemented earlier in a wider row crop than in more closely spaced crops (Knezevic *et al*. 2003). Similarly, in glyphosate-resistant soybean studies, the critical period of weed removal occurred earlier with wider row spacings, possibly due to a larger weed biomass (Mulugeta and Boerboom 2000). The authors argued that there is no single critical time of weed removal, which varies between seasons even with constant row spacing and tillage system. When substantial weed emergence occurs throughout the season, multiple weed removal events may be necessary (Mohler 2001).

If weed control is implemented too late then large weeds compete with the crop for resources before control (Murphy *et al*. 1996; Hashem *et al*. 2005). In Western Australia, annual ryegrass numbers were reduced by 50% using cultivation with wide sweep points late in the season (Hashem *et al*. 2005). Lupin yield was no different than the uncultivated control and it was likely that cultivation treatments were undertaken too late to minimise the competitive effect of the annual ryegrass on the crop, and that plants tended to clump, resulting in a large number of transplants.

The timing of weed emergence and their critical periods of removal vary with species (Forcella *et al*. 2000; Hilgenfeld *et al*. 2004*a*; Walker *et al*. 2006), allowing some of them to escape control and set seed. In glyphosate-resistant soybean in Minnesota, late weed emergence was the main reason for weed control escape (Scursoni *et al*. 2007). In Western Australia, many of the grass weeds including barley grass (*Hordeum leporinum* Link.), annual ryegrass, and wild oats (*Avena fatua* L.), tend to emerge in the first month of the season break, while some broad-leafed weeds such as wild radish germinate throughout (Peltzer and Matson 2002). Wild radish is predominantly rainfall dependent and will germinate with each rainfall event, compared with annual ryegrass, which also requires temperature cues (Forcella 1984). Similarly, in Queensland, common sowthistle (*Sonchus oleraceus* L.) is rainfall event dependent and will germinate throughout the whole year (Widderick *et al*. 2004). Late canopy closure favours later geminating species such as common sowthistle (Widderick *et al*. 2004). The timing of glyphosate application in glyphosate-resistant crop systems depends on the predominant species as well as on the height and density of the weeds (Dalley *et al*. 2004), but it may also be governed by permitted windows of use, usually related to crop growth stages. For example, glyphosate can only be applied twice before the unfolding of the fifth true leaf in Roundup Ready cotton in Australia (Taylor and Charles 2002).

The timing of inter-row weed removal is also dependent on the control method. Herbicides can be less effective on older weeds (Moore and Moore 2007) and tillage may stimulate germination early in the season or fail to control older weeds (Peltzer *et al*. 2007). Timing of cultivation after crop emergence is dependent on the best time to control the major weed species at a site. Success depends on the relative growth of crop to weed as selectivity depends on relative growth of weeds to crop. As the time to removal becomes earlier the reduction in crop stand is likely to be greater, as small crop plants may be smothered by soil throw (Hashem *et al*. 2008). Research indicates that if cultivation were used as the exclusive weed control measure, several passes of cultivation would be required (Mt. Pleasant *et al*. 1994). In winter wheat, two passes with a hoe, early and late, were particularly effective on volunteer oilseed rape (Melander *et al*. 2003) and, while late emerging weeds have a minimal effect on maize yield, harvest efficiency and grain contamination may become a concern (Burnside 1998; Donald 2000).

Crop damage

Crop damage from weed control in wide row systems may be due to physical damage from tillage and mowing implements or shields traversing the row, herbicide drift, movement of herbicide in the soil, movement of soil or trash containing herbicide, and concentration of herbicide due to local topography such as furrows. In the early adoption phase there is likely to be significant damage as machinery, herbicides, rates, methods, and times of application, and planting techniques are fine-tuned. Soil types, rainfall, and cropping systems involving various levels of trash or disturbance may also affect the amount of crop damage (Moore and Moore 2007). Minimum crop damage and maximum yields will depend on developing systems with several interacting factors. Hashem *et al*. (2008) recorded much less crop damage (1%) by Spray.Seed® sprayed on the inter-row weeds by spray-shield compared with 6–12% by glyphosate and 39–55% by inter-row cultivation.

Unregistered herbicide usage issues

Application of herbicides to the inter-row area potentially allows the use of alternative herbicides or high rates that are normally too damaging for overall spraying of the crop. This may require analysis of herbicide residues and, potentially, the adjustment of maximum residue limits for the crop plant. In some cases a new use pattern will need to be added to the label (APVMA 2007). This has implications for growers producing quality-assured crops.

For herbicides that are registered for use on the crop as an overall application, the use on the inter- or intra-row is not expected to be an issue unless there are State regulations prohibiting the use of reduced rates per hectare.

Herbicide resistance

Glyphosate is an important non-selective herbicide, controlling a wide spectrum of weeds. Some species are naturally tolerant of glyphosate and, up until 10 years ago, there were no reported cases of evolved glyphosate resistance. Evolved resistance to glyphosate has now been confirmed in 13 different species in 14 countries (Heap 2008). At present, two different mechanisms have been identified that endow glyphosate resistance: a weak target site mutation and a reduced glyphosate translocation mechanism. In Australia, evolved resistance to glyphosate has been found in 58 populations of annual ryegrass (Powles *et al*. 1998; Pratley *et al*. 1999; Preston 2007) with both mechanisms (Powles and Preston 2006). There have also been two confirmed cases of glyphosate resistance in barnyard grass (*Echinochloa cruss-galli* [L.] Beauv.) in northern New South Wales (Storrie 2008).

Resistance to glyphosate is known to evolve where selection pressure is high (Powles and Preston 2006). Glyphosate is commonly used in wide row systems and in Roundup Ready® cotton, and there are often repeated applications throughout the growing season and during the preceding and following fallow periods, particularly in the north-eastern areas of Australia (Osten *et al*. 2007). This increased usage is likely to result in a rapid development of glyphosate resistance. More accurate spraying techniques (e.g. 2 cm accuracy spraying), inter-row cultivation, use of herbicides with alternative modes of action such as Spray.Seed®, and understanding of the population and seedbank dynamics may help minimise the risk of such resistance development.

Weed species shift

Evolved resistance or natural tolerance of the inter-row weeds to broad spectrum herbicides used in the inter-row, coupled with avoidance due to application timing, may result in a change in the weed composition (Wicks *et al*. 2000; Hilgenfeld *et al*. 2004*b*; Nandula *et al*. 2005).

In a 10-year wheat fallow rotation in New South Wales where glyphosate was the main herbicide used in the fallow period, 17 weed species were glyphosate tolerant at the commonly used rates and needed other herbicides to control them (Wicks *et al*. 2000). These included common sowthistle (*Sonchus oleraceus* L.), native millet (*Panicum decomposium* R.Br.), variegated thistle (*Silybum marianum* (L.) Gaert.), dandelion (*Hypochaeris glabra* L.), spear thistle (*Cirsium vulgare* (Savi) Ten.), prickly lettuce (*Lactuca* spp.), fleabane (*Conyza* spp.), saffron thistle (*Carthamus lanatus* L.), St Barnaby's thistle (*Centaurea solstitialis* L.), windmill grass (*Chloris truncata* R.Br.), turnip weed (*Rapistrum ragosum* L.), bladder ketmia (*Hibiscus trionum* L.), pigweed (*Portulaca oleracea* L.), field bindweed (*Convolvulus arvensis* L.), awnless barnyard grass (*Echinochloa colona* (L.) Link), stinkgrass (*Eragrostis cilianensis* (All) Vignola ex Janch.), and wireweed (*Polygonum aviculare* L.). Some weed species can be tolerant or have developed resistance to other non-selective herbicides that may be used in the inter-row. Paraquat resistance has been found in *Conyza* spp. (Ye and Gressel 1994) and *Hordeum glaucum* Steud. (Powles 1986).

Continual application of non-selective herbicides such as glyphosate may select for tolerant weeds, resulting in their eventual domination (Smeda and Schuster 2002; Scursoni *et al*. 2007). Lessons can be learnt from glyphosate-resistant crops with multiple glyphosate applications where weed communities respond to selection pressure (Harker *et al*. 2005; Culpepper 2006). Weed scientists across the US have indicated that weed shifts are occurring in glyphosate-resistant crops and are of economic concern (Culpepper 2006). Most of these weeds are tolerant to glyphosate and it is likely that the advent of glyphosate-resistant crops and increased utilisation of glyphosate in conservation tillage were responsible.

Avoidance due to the timing of the treatment plus herbicide tolerance are likely to be the major contributors to changes in weed species (Hilgenfeld *et al*. 2004*b*; Scursoni *et al*. 2007). Ivy-leaf morning glory (*Ipomea hederacea* Jacq.) survived glyphosate application due to late emergence and tolerance, which could culminate in its domination in glyphosate-resistant soybeans. Late weed emergence was the main reason for weed escapes in glyphosate-resistant soybean. *Chenopodium album* (L.) had a long period of emergence while black nightshade (*Solanum ptycanthum* Dunal) emerged late; both were recorded as escapes in four locations in Minnesota, USA (Scursoni *et al*. 2007). Weeds such as *Fallopia convolvulus* germinating later in the season in wide row systems may often carry over into the summer fallow in wide row cereal systems in northern New South Wales (Storrie *et al*. 2007). Timing of herbicide application may also affect herbicide efficacy when used inter-row. Large weeds may be more herbicide tolerant and late application can allow regrowth of some weeds. Wild radish is reported to be hard to kill after the 4-leaf stage (Moore 2001). A long-term study on the induction of glyphosate resistance in annual ryegrass showed that continuous application of glyphosate at a low rate (250 g a.i./ha.year at the 3- to 4-leaf stage of annual ryegrass) has resulted in massive increases of marshmallow (*Malva parviflora* L.) and Indian hedge mustard (*Sisymbrium orientale*) with a simultaneous reduction in annual ryegrass (A. Hashem *et al*., unpubl. data).

Cultivation as a weed control method also selects for different species (Blackshaw *et al*. 1994; Blackshaw 2005). Deep-rooted plants and vigorous early season weeds were more difficult to control, with a greater proportion of transplants (Mohler *et al*. 1997). Tap-rooted species have poorer tolerance to below-ground cultivation and weeds establishing from roots or rhizomes were more effectively controlled by hoeing than harrowing (Melander *et al*. 2003). Generally, weeds germinating from seed were controlled best by herbicide application compared with cultivation (Mohler *et al*. 1997). Weed communities in systems with inter-row cultivation were more diverse than those in conventional no-tillage (Swanton *et al*. 2006).

Cultivation may also stimulate weed germination in some weed species. Germination of annual ryegrass, wild radish, wild oat, wall fumitory (*Fumaria muralis* Sonder ex Koch), and paradoxa grass (*Phalaris paradoxa* L.) is stimulated by shallow cultivation (Peltzer and Matson 2002; Taylor and Charles 2002). A mid-season inter-row cultivation stimulated wild radish emergence by 50% above the control (Peltzer *et al*. 2007). This may reduce crop yields, especially when water is limiting, and result in a massive weed seedset to be available the following season.

Increasing the row spacing may select for different species by altering the light, moisture, and nutrient status and subsequently their competitive ability (Donald 1963). Where light is limiting, broad-leafed weeds can be more competitive than grasses with a more spreading growth form and more horizontal leaves (Aldrich and Kremer 1997). Competition for nitrogen and water is largely determined by the root system. Plants with deep vertical root systems can compete strongly for limiting water and annual grasses generally have fibrous roots and are efficient at taking up nutrients. Annual ryegrass absorbs nitrogen over a much greater part of its growth cycle, while wheat stops absorbing nitrogen after the 3-leaf stage (Forcella 1984). Plants with extensive lateral root growth can compete for resources with other plants even if growing only between the rows.

Crop rotations

At present the main crops suitable for inter-row weed control in Australia are legumes in southern Australia and sorghum, sunflower, chickpea, and dryland cotton in the northern regions, due to their upright structure and ability to withstand wide row spacings.

In southern Australia, legumes are put into the rotation to provide a break from cereal and canola crops and to improve soil nitrogen. Cereals and canola crops generate the most profit within the rotation but cannot be economically grown in the same row spacings. This is also the case in northern Australia where sorghum, sunflower, and cotton are grown on 1 m row spacings with wheat re-cropped at 50 cm. This has major implications on how to manage the rotations and fit the wide spaced legumes and other crops. For example, in Western Australia, narrow-leafed lupins can be grown in 72 cm row spacing using precision agriculture and inter-row weed control techniques. Cereals such as wheat and barley can then be sown in 36 cm spacings. The positioning of rows for cereal growth needs to be considered carefully. Sowing row upon row could develop ribbons of fertility where lupins were grown in the previous season, especially if fertiliser was applied directly to the row and not broadcast. The wheat row sown in the middle or skip row would have a different nutrient status and be difficult to fertilise differently, especially with current technology. It is likely that the moisture status of the rows for cereal growth would also be different as there is sometimes a reduction in the depth of moisture under the rows grown in the previous season. This would depend on the density of the plants and their lateral exploration.

There could also be problems with stubble handling and disease problems when sowing row upon row. Research at 44 sites in 2005 showed that sowing between previous winter cereal rows decreases the severity (by an average of 51%) and incidence (by an average of 45%) of crown rot in following cereal crops. Inter-row sowing was effective at reducing crown rot in bread wheat, barley, and durum varieties but it does not appear to reliably reduce levels of common root rot (Simpfendorfer *et al*. 2006). Shifting the row slightly may avoid the stubble and disease problems but studies need to be done to prove how far.

Economic risks

There are economic risks associated with increased row spacing for weed control. Besides the possibility of reduced yields, introducing the technology required for inter-row weed control can be very expensive. In Western Australia the use of shielded spray technology in a wheat–lupin rotation is only profitable if used to successfully control resistant weeds (Peek *et al*. 2006) and is of most assistance where the yields are high.

Options to reduce risk and improve weed management

Modelling herbicide resistance

A major unquantified risk in wide row cropping is enhanced development of resistance to non-selective herbicides. Resistance to non-selectives has developed more slowly than resistance to many selective herbicides. This is partly because non-selective herbicides are typically applied before all weeds have germinated, so selection pressure is lower (Neve *et al*. 2003). Inter-row spraying of non-selectives in wide row systems will allow these herbicides to be used later and consequently should increase the risk. To date, there has been no simulation modelling of the risk of developing herbicide resistance specifically in wide row systems; however, a model developed by Thornby *et al*. (2006) determines the risk of glyphosate resistance evolution in summer grasses in Australia's northern grain region. The early model predicted fairly rapid evolution of glyphosate-resistant barnyard grass in a wheat and sorghum rotation.

Complicating factors include the fact that different subpopulations of weeds are being treated differently, but pollen and seed move between these subpopulations. Herbicide resistance models exist that include more than one interacting weed population. These include the spatially explicit model developed by Richter *et al*. (2002). In the situations considered in that case, different subpopulations were spatially segregated, while for wide row systems the subpopulations are intimately mixed. However, some of the methodology used in that model is applicable to simulation of risk in wide row systems.

Treatment of the inter-row only is analogous in some ways to leaving untreated refuges, a strategy sometimes used to reduce the rate of development of insecticide resistance. There are numerous differences between the processes that affect herbicide and insecticide resistance, including differences in mobility of the pest organisms and differences in the genetics that confer pesticide resistance. However, modelling of spatial factors that affect development of insecticide resistance is more advanced than is the case for herbicide resistance, and some modelling principles are transferable. Relevant models of insecticide resistance include those developed by Ives and Andow (2002), Storer *et al*. (2003), and Pertoldi and Topping (2004).

Site-specific weed management

Traditionally, weeds are controlled by applying herbicides uniformly over the entire field or by shielded sprayer to the inter-rows. As weeds generally grow in patches (Marshall 1988; Cardina *et al*. 1997), applying herbicide on weed-free locations results in excessive use of herbicides, with significant economic and environmental effects. This has led to the development of site-specific weed management technologies in the past 15 years, which are now at a stage that they can be adopted by farmers. Such technologies are particularly suitable to wide row cropping systems, which can limit application of appropriate herbicide, in a desired amount, to weed-growing areas only.

There are basically two approaches to site-specific weed management: sensor-based and map-based. The sensor-based method makes use of on-the-go sensors to identify weeds and apply herbicide instantaneously in one operation (Felton *et al*. 1991; Hanks and Beck 1998; Tian *et al*. 1999; Hummel and Stoller 2002). The sensors work by detecting light at red (650 nm) and near-red infrared (850 nm) wavelengths. However, the present sensors can only successfully differentiate between soil and vegetation and thus are either suitable for fallow fields or row-crop production systems. These systems can have problems, though, due to the shape of the weed leaf, with small weeds being difficult to detect and larger weeds not getting an adequate dose. A dual boom (one with a standard boom with a lower herbicide rate and another activated by optical sensors) was found to be useful in reducing these problems (Wicks *et al*. 1998).

The map-based method is a 2-step process: weed maps are first prepared to develop variable-rate application plans, which are then used by DGPS (Differential Global Positioning System)-controlled sprayers (Brown *et al*. 2000; Gerhards and Oebel 2006) to apply herbicides to only those locations where weeds are present above economic threshold values. Several state-of-the-art technologies (Medlin *et al*. 2000; Lamb and Brown 2001; Jurado-Expósito *et al*. 2003; Yang *et al*. 2003; Thorp and Tian 2004; Shaw 2005) discriminate between crop and weeds in agricultural fields for preparation of weed maps. A recent development of an automated method for generating weed maps using near-ground images is specifically useful for wide row cropping systems (Hague *et al*. 2006).

Compared with uniform application, patch spraying technology has shown substantial reductions in herbicide usage (Gerhards and Christensen 2003; Tredaway-Ducar *et al*. 2003; Nordmeyer 2006) and increased net returns (Medlin and Shaw 2000; Timmermann *et al*. 2003; Lamastus-Stanford and Shaw 2004). There is also a huge potential to minimise environmental risks, such as ground and surface water pollution, and to avoid herbicide resistance development with efficient and effective use of herbicides under site-specific management of weeds (Oriade *et al*. 1996; Khakural *et al*. 1998).

Precision guided mechanical weed control

The increasing impact of herbicide-tolerant and hard-to-kill weeds, together with some environmental and safety concerns, has led to renewed interest in mechanical weed control (Jones and Blair 1996; Bond and Grundy 2001). At the same time, precision field guidance has developed to the point where the performance limitations of traditional inter-row cultivation no longer apply (Slaughter *et al*. 1999; Wilson 2000). The precision GPS guidance units can now operate to within ±2 cm indefinitely at normal field speeds. Intermittent use of non-herbicide weed management would help farmers to cope with herbicide escapes, and slow the development of herbicide-tolerant species.

Mechanical weed control demands shallow soil disturbance as close to the row as possible. The most obvious example of precision weed control is where the human eye and hand identify the weed and precisely position a hoe to destroy it. Where the crop is planted and managed with great precision, spatial selectivity (i.e. identification of weeds as plants outside the row) can achieve a similar result. With the availability of high-precision guidance systems, the width of the crop strip within which weeds survive becomes smaller, resulting in greater control of weeds competing with crop.

A recent study conducted in Australia (Bromet 2006) concluded that Real Time Kinematic Global Positioning System (RTK GPS)-controlled mechanical cultivation resulted in nearly 90% weed kill, with very minor crop damage in sorghum grown under a wide row cropping system. Another approach to control weeds and possibly by-pass herbicide resistance has been through a combination of mechanical and chemical weed control, where weeds between the rows are controlled by mechanical cultivation and the remaining small fraction of the row is treated with herbicides (Mulder and Doll 1993; Buhler *et al*. 1995; Hanna *et al*. 2000). In Western Australia, use of Spray.Seed® or knockdown-based tank mixes as alternatives to glyphosate for inter-row weed control with spray-shield provided the same as, or even higher, weed control and grain yield of narrow-leafed lupins as glyphosate application at a farmer's paddock using the farmer's commercial equipment (Hashem *et al*. 2007).

Conclusions

Wide row cropping is useful for the following four reasons: water conservation; stubble handling; pest, disease, and frost management; and facilitation of certain weed control practices. Wide row cropping, particularly in summer crops, is a risk-minimisation tool designed for use in poor seasons and in marginal cropping areas where water is a major limiting factor of production. The extent of water extraction throughout the wide inter-row space depends on crop root length density and the balance between the demand for and supply of water. When used in good seasons, some yield is sacrificed but water remaining after harvest begets the opportunity for double cropping provided the soil is capable of storing it. Under wide row spacing systems, weeds must be controlled to preserve water and hence the purpose of implementing the system in the first place. The wide row cropping system also minimises the general problems associated with stubble management encountered under the traditional narrow row spacing during the sowing operation, as well as the extent of crop damage due to pests, diseases, and frost.

Wide-row spacings facilitate opportunities for zonal and site-specific weed management and offer opportunities to make best use of new and emerging technologies for weed control. Wide row cropping systems allow the integration of chemical and mechanical weed control methods to achieve optimum weed control with lower risks of herbicide resistance and higher environmental benefits. Chemical-based site-specific weed management can reduce the physical amount of herbicide applied to paddocks, which means that reduced overall herbicide inputs are less available for movement and run-off. This ultimately leads to cleaner, greener agriculture. The site zonal system also allows better nutrient placement in favour of the crop. This reduces inputs, which in turn reduces nutrient run-off.

Crop competition is reduced with wider rows, so weed management relies more on herbicides and tillage. This reliance brings risks such as herbicide resistance, species shifts and/or changes in species dominance, crop damage, and increased costs (yield losses and more expensive weed management technology); some of these risks are more easily managed than others. The timing of inter-row mechanical weed control is extremely important in relation to weed kill, crop damage, and regrowth of weeds, and this subject needs further investigation.

Acknowledgments

This study was supported by the CRC for Weed Management. Thanks to Steve Walker for his constructive comments on the manuscript. An abbreviated version of this paper was presented at the 16th Australian Weeds Conference in Cairns, Australia, in May 2008.

References

Abu-Hamdeh NH (2003) Effect of weed control and tillage system on net returns from bean and barley production in Jordan. *Canadian Biosystems Engineering* **45**, 223–228.

Aldrich RJ, Kremer RJ (1997) 'Principles in weed management.' (Iowa State University Press: Ames, IA)

Allmaras RR, Dowdy RH (1985) Conservation tillage systems and their adoption in the United States. *Soil & Tillage Research* **5**, 197–222. doi: 10.1016/0167-1987(85)90030-3

Amador-Ramirez MD, Wilson RG, Martin AR (2001) Weed control and dry bean (*Phaseolus vulgaris*) response to in-row cultivation, rotary hoeing and herbicides. *Weed Technology* **15**, 429–436. doi: 10.1614/0890-037X(2001)015[0429:WCADBP]2.0.CO;2

Amjad M, Green AHS, Riethmuller GP, Jarvis RJ (1996) Effects of a range of seeding systems on lupin establishment and yield under minimum soil disturbance and maximum stubble retention conditions in Western Australia. In 'Engineering in agriculture and food processing'. Gatton, Qld. p. SEAg 96/025. (University of Queensland: Brisbane)

Anderson WK, Barclay J (1991) Evidence for differences between three wheat cultivars in yield response to plant population. *Australian Journal of Agricultural Research* **42**, 701–713. doi: 10.1071/AR9910701

Anderson WK, Garlinge JR (2000) 'The wheat book – principles and practice.' (Agriculture Western Australia: Perth, W. Aust.)

APVMA (2007) Australian Pesticides and Veterinary Medicines Authority. Available at: www.apvma.gov.au

Baumann DT, Slembrouck I (1994) Mechanical and integrated weed control systems in row crops. *Acta Horticulturae* **372**, 245–251.

Beech DF, Leach GJ (1989) Effect of plant density and row spacing on the yield of chickpea (cv. Tyson) grown on the Darling Downs, south-eastern Queensland. *Australian Journal of Experimental Agriculture* **29**, 241–246. doi: 10.1071/EA9890241

Belfield S, Serafin L, McCaffery D (2006) Sunflower: NSW planting guide 2006–2007. NSW Department of Primary Industries, Orange, NSW.

Blackshaw RE (2005) Tillage intensity affects weed communities in agroecosystems. In 'Invasive plants: ecological and agricultural aspects'. (Ed. Inderjit) pp. 209–221. (Birkhäuser: Basel, Switzerland)

Blackshaw RE, Molnar LJ (2004) Nitrogen fertiliser timing and application method affect weed growth and competition with spring wheat. *Weed Science* **52**, 614–622. doi: 10.1614/WS-03-104R

Blackshaw RE, Molnar LJ, Larney FJ (2005) Fertiliser, manure and compost effects on weed growth and competition with winter wheat in western Canada. *Crop Protection* **24**, 971–980. doi: 10.1016/j.cropro.2005.01.021

Blackshaw RR, Larney FO, Lindwall CW, Kozub GC (1994) Crop rotation and tillage effects on weed populations on the semi-arid Canadian prairies. *Weed Technology* **8**, 231–237.

Bond W, Grundy C (2001) Non-chemical weed management in organic farming. *Weed Research* **41**, 383–405. doi: 10.1046/j.1365-3180.2001.00246.x

Bromet N (2006) Weed management using GPS steering. PhD Thesis, University of Queensland, Australia.

Brown RB, Bennett K, Goudy H, Tardif F (2000) Site-specific weed management with a direct-injection precision sprayer. In 'Proceedings of the American Society of Agricultural Engineers'. St. Joseph, Michigan. (ASAE)

Buhler DD, Doll JD, Proost RT, Visocky MR (1995) Integrating mechanical weeding with reduced herbicide use in conservation tillage corn production systems. *Agronomy Journal* **87**, 507–512.

Burgis M (2002) Comparing new herbicide options using shielded sprayers. In 'The Australian cotton grower'. p. 20. (Greenmount Press)

Burnside O (1998) Mechanical and chemical weed control systems for kidney bean (*Phaseolus vulgaris*). *Weed Technology* **12**, 174–178.

Bwye AM, Jones RAC, Proudlove W (1999) Effects of different cultural practices on spread of cucumber mosaic virus in narrow-leafed lupins (*Lupinus angustifolius*). *Australian Journal of Agricultural Research* **50**, 985–996. doi: 10.1071/AR98202

Cardina J, Johnson GA, Sparrow DH (1997) The nature and consequences of weed spatial distribution. *Weed Science* **45**, 364–373.

Carter MR (1994) A review of conservation tillage strategies for humid temperate regions. *Soil & Tillage Research* **31**, 289–301. doi: 10.1016/0167-1987(94)90037-X

Cochran VL, Morrow LA, Schirman RD (1990) The effect of N placement on grass weeds and winter wheat responses in three tillage systems. *Soil & Tillage Research* **18**, 347–355. doi: 10.1016/0167-1987(90)90119-X

Collins M, Roche J (2002) Weed control in lupins using a new spray shield and other row crop techniques. In 'Weeds threats now and forever. Proceedings of the 13th Australian Weeds Conference'. Perth, W. Aust. (Eds H Spafford Jacob, J Dodd, JH Moore) pp. 484–487. (Plant Protection Society of Western Australia: Perth, WA)

Collins R, Reid D, Cox H (2006) Matching sorghum rows to rainfall outlook. *Australian Farm Journal* **16**(2), 37–38.

Crabtree B, Fosbery G, Roe A, Collins M, Beckett M (2002) Lupin wider row spacing data and observations. In 'Crop Updates, Technical Information for Agribusiness'. p. 9. (Department of Agriculture: Perth, W. Aust.)

Culpepper AS (2006) Glyphosate-induced weed shifts. *Weed Technology* **20**, 277–281. doi: 10.1614/WT-04-155R.1

Dalley CD, Kells JJ, Renner KA (2004) Effect of glyphosate timing and row spacing on corn (*Zea mays*) and soybean (*Glycine max*) yields. *Weed Technology* **18**, 165–176. doi: 10.1614/02-150A

Donald CM (1963) Competition among crop and pasture plants. *Advances in Agronomy* **15**, 1–118. doi: 10.1016/S0065-2113(08)60397-1

Donald WW (2000) Alternative ways to control weeds between rows in weeded check plots in corn (*Zea mays*) and soybean (*Glycine max*). *Weed Technology* **14**, 36–44. doi: 10.1614/0890-037X(2000)014[0036:AWTCWB]2.0.CO;2

Donald WW, Kitchen NR, Sudduth KA (2001) Between row mowing and banding of herbicide to control annual weeds and reduce herbicide use in no till soybean (*Glycine max*) and corn (*Zea mays*). *Weed Technology* **15**, 576–584. doi: 10.1614/0890-037X(2001)015[0576:BRMBHT]2.0.CO;2

Egley GH (1986) Simulation of weed seed germination in soil. *Reviews of Weed Science* **2**, 67–89.

Felton WL, Doss AF, Nash PG, McCloy KR (1991) A micro-processor controlled technology to selectively spot spray weeds. In 'Symposium on Automated Agriculture for the 21st Century'. pp. 427–432. (American Society of Agricultural Engineers: St. Joseph, MI)

Felton WL, Haigh BM, Harden S (2004) Comparing weed competition in chickpea, fababean, canola and wheat. In 'Proceedings 14th Australian Weed Conference'. pp. 304–307. (Weed Society of New South Wales: Wagga Wagga, NSW)

Felton WL, Marcellos H, Murison RD (1996) The effect of row spacing and seeding rate on chickpea yield in northern New South Wales. In 'Proceedings 8th Australian Weeds Conference'. pp. 251–253. (Weed Society of Queensland: Toowoomba, Qld)

Fischer RA, Miles RE (1973) The role of spatial pattern in competition between crop plants and weeds. A theoretical analysis. *Mathematical Biosciences* **18**, 335–350. doi: 10.1016/0025-5564(73)90009-6

Forcella F (1984) Wheat and ryegrass competition for pulses of mineral nitrogen. *Australian Journal of Experimental Agriculture* **24**, 421–425. doi: 10.1071/EA9840421

Forcella F, Benech Arnold RL, Sanchez R, Ghersa CM (2000) Modelling seedling emergence. *Field Crops Research* **67**, 123–139. doi: 10.1016/S0378-4290(00)00088-5

Freebairn DM, Loch RJ, Cogle AL (1993) Tillage methods and soil and water conservation in Australia. *Soil & Tillage Research* **27**, 303–325. doi: 10.1016/0167-1987(93)90074-Y

French B (2004) Effect of environment to lupin yield response to row spacing. In 'Crop Updates, Technical Information for Agribusiness'. pp. 31–32. (Department of Agriculture: Perth, W. Aust.)

French B, Wahlsten L (2003) Influence of row spacing on water stress and water use of lupins. In 'Crop Updates, Technical Information for Agribusiness'. pp. 22–23. (Department of Agriculture: Perth, W. Aust.)

Gerhards R, Christensen S (2003) Real-time weed detection, decision making and patch spraying in maize, sugarbeet, winter wheat and winter barley. *Weed Research* **43**, 385–392. doi: 10.1046/j.1365-3180.2003.00349.x

Gerhards R, Oebel H (2006) Practical experiences with a system for site-specific weed control in arable crops using real-time image analysis and GPS-controlled patch spraying. *Weed Research* **46**, 185–193. doi: 10.1111/j.1365-3180.2006.00504.x

Hague T, Tillett ND, Wheeler H (2006) Automated crop and weed monitoring in widely spaced cereals. *Precision Agriculture* **7**, 21–32. doi: 10.1007/s11119-005-6787-1

Hanks JE, Beck JL (1998) Sensor-controlled hooded sprayer for row crops. *Weed Research* **12**, 308–314.

Hanna HM, Hartzler RG, Erbach DC (2000) High-speed cultivation and banding for weed management in no-till corn. *Applied Engineering in Agriculture* **16**, 359–365.

Hansson D, Ascard J (2002) Influence of developmental stage and time of assessment on hot water weed control. *Weed Research* **42**, 307–316. doi: 10.1046/j.1365-3180.2002.00290.x

Harker KN, Clayton GW, Blackshaw RE, O'Donovan JT, Lupwayi NZ, Johnson EN, Gan Y, Zentner RP, Lafond GP, Byron Irvine R (2005) Glyphosate-resistant spring wheat production system effects on weed communities. *Weed Science* **53**, 451–464. doi: 10.1614/WS-04-105R1

Harries M (2005) Combining cultural and shielded sprayer herbicide application for weed management. In 'Crop Updates, Technical Information for Agribusiness'. p. 19. (Department of Agriculture: Perth, W. Aust.)

Harries M, French B, Owen D (2005) Lupin seed rate by wide row spacing. In 'Crop Updates, Technical Information for Agribusiness'. pp. 22–26. (Department of Agriculture: Perth, W. Aust.)

Harris G (1999) Cotton. In 'Crop Management Notes – Central Queensland'. (Queensland Department of Primary Industries: Brisbane, Qld)

Hashem A, Douglas A, Pathan S, Peltzer S (2008) Control and seed production of annual ryegrass in wide row lupins in WA wheatbelt. In '16th Australian Weeds Conference'. (Ed. V Osten) (Weed Society of Queensland: Cairns, Qld)

Hashem A, Fulwood R, Roberts C (2007) Inter-row weed control in wide-row lupins using knockdown-based tank mixes. In 'Crop Updates, Technical Information for Agribusiness'. (Department of Agriculture: Perth, W. Aust.)

Hashem A, Nicholson D, Bowran D, Pathan S (2005) Non-selective herbicide molecules for inter-row weed control in wide row lupins. In 'Crop Updates, Technical Information for Agribusiness'. pp. 32–34. (Department of Agriculture: Perth, W. Aust.)

Heap IM (2008) The international survey of herbicide resistant weeds. Available at: www.weedscience.com

Hilgenfeld KL, Martin AR, Mortensen DA, Mason SC (2004*a*) Weed management in a glyphosate resistant soybean system: Weed emergence patterns in relation to glyphosate treatment timing. *Weed Technology* **18**, 277–283. doi: 10.1614/WT-03-042R1

Hilgenfeld KL, Martin AR, Mortensen DA, Mason SC (2004*b*) Weed management in a glyphosate resistant soybean system: weed species shift. *Weed Technology* **18**, 284–291. doi: 10.1614/WT-03-045R1

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. *Weed Science* **54**, 38–46. doi: 10.1614/WS-05-011R.1

Hodges A, Goesch T (2006) Australian farms natural resource management in 04/05. ABARE Research Report 06.12, Australian Government Department of Agriculture, Fisheries and Forestry, Canberra. Available at: www.abareconomics.com/publications_html/crops/crops_06/nrm_ausfarmers.pdf

Hummel JW, Stoller EW (2002) On-the-go weed sensing and herbicide application for the northern cornbelt. In 'Proceedings of the American Society of Agricultural Engineers'. Paper No. 02-1021. (ASAE: St. Joseph, MI)

Ives AR, Andow DA (2002) Evolution of resistance to Bt crops: directional selection in structured environments. *Ecology Letters* **5**, 792–801. doi: 10.1046/j.1461-0248.2002.00392.x

Jensen RK, Rasmussen J, Melander B (2004) Selectivity of weed harrowing in lupin. *Weed Research* **44**, 245–253. doi: 10.1111/j.1365-3180.2004.00396.x

Jettner RJ, Siddique KHM, Loss SP, French RJ (1999) Optimum plant density of desi chickpea (*Cicer arientinum* L.) increases with increasing yield potential in south-western Australia. *Australian Journal of Agricultural Research* **50**, 1017–1025. doi: 10.1071/AR98179

Jones PA, Blair AM (1996) Mechanical damage to kill weeds. In 'Proceedings of 2nd International Weed Control Congress'. Copenhagen, Denmark. pp. 949–954. (Springer: The Netherlands)

Jones RAC (1994) Effect of mulching with cereal straw and row spacing on spread of bean yellow mosaic potyvirus into narrow-leafed lupins (*Lupinus angustifolius*). *Annals of Applied Biology* **124**, 45–58. doi: 10.1111/j.1744-7348.1994.tb04114.x

Jordan N (1993) Prospects for weed control through crop interference. *Ecological Applications* **3**, 84–91. doi: 10.2307/1941794

Jurado-Expósito M, López-Granados F, Atenciano LG, García-Torres L, González-Andújar JL (2003) Discrimination of weed seedlings, wheat (*Triticum aestivum*) stubble and sunflower (*Helianthus annuus*) by near-infrared reflectance spectroscopy (NIRS). *Crop Protection* **22**, 1177–1180. doi: 10.1016/S0261-2194(03)00159-5

Khakural B, Robert P, Mulla D, Oliveira R, Johnson G, Koskinen W (1998) Site-specific herbicide management for preserving water quality. In 'Proceedings of the 4th International Conference on Precision Agriculture'. St Paul, MN. (Eds PC Robert, RH Rust, WE Larson) pp. 1719–1731. (ASA/CSSA/ASSA: Madison, WI)

Knezevic SZ, Evans SP, Mainz M (2003) Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). *Weed Technology* **17**, 666–673. doi: 10.1614/WT02-49

Kouwenhoven JK (1997) Intra-row mechanical weed control possibilities and problems. *Soil & Tillage Research* **41**, 87–104. doi: 10.1016/S0167-1987(96)01076-8

Laflen JM, Baker JL, Hartwig RO, Buchele WF, Johnson HP (1978) Soil and water loss from conservation tillage systems. *Transactions of the American Society of Agricultural Engineers* **21**, 881–885.

Lafond GP (1994) Effects of row spacing, seeding rate and nitrogen on yield of barley and wheat under zero-till management. *Canadian Journal of Plant Science* **74**, 703–711.

Lamastus-Stanford FE, Shaw DR (2004) Evaluation of site-specific weed management implementing the herbicide application decision support system (HADSS). *Precision Agriculture* **5**, 411–426. doi: 10.1023/B:PRAG.0000040808.78546.d5

Lamb DW, Brown RB (2001) Remote sensing and mapping of weeds in crops. *Journal of Agricultural Engineering Research* **78**, 117–125. doi: 10.1006/jaer.2000.0630

Lemerle D, Gill GS, Murphy CE, Walker SR, Cousens RD, Mokhtari S, Peltzer S, Coleman R, Luckett DJ (2001) Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Australian Journal of Agricultural Research* **52**, 527–548. doi: 10.1071/AR00056

Maling AM, Roberson M, Isbister B, Bowden WJ (2007) Farmer trials and experiences prove the adoption of precision agriculture technology is profitable in Western Australia. In '5th Australian Controlled Traffic Farming and Precision Agriculture Conference'. UWA, Perth, W. Aust. (Ed. G Hamilton) pp. 110–117.

Marshall EJP (1988) Field-scale estimates of grass weed populations in arable land. *Weed Research* **28**, 191–198. doi: 10.1111/j.1365-3180.1988.tb01606.x

Medlin CR, Shaw DR (2000) Economic comparison of broadcast and site-specific herbicide applications in nontransgenic and glyphosate-tolerant *Glycine max*. *Weed Science* **48**, 653–661. doi: 10.1614/0043-1745(2000)048[0653:ECOBAS]2.0.CO;2

Medlin CR, Shaw DR, Gerard PD, LaMastus FE (2000) Using remote sensing to detect weed infestation in *Glycine max*. *Weed Science* **48**, 393–398. doi: 10.1614/0043-1745(2000)048[0393:URSTDW]2.0.CO;2

Melander B (2006) Physical weed control in Europe: current achievements and future directions. *Phytoma* **591**, 26–29.

Melander B, Cirujeda A, Jorgensen MH (2003) Effects of inter-row hoeing on weed growth and yield of winter wheat. *Weed Research* **43**, 428–438. doi: 10.1046/j.0043-1737.2003.00359.x

Minkey D, Riethmuller G, Hashem A (1999) Effect of row spacing and seeding rate of wheat on the emergence and competitive ability of annual ryegrass in a no-tillage seeding system. In 'Crop Updates, Technical Information for Agribusiness'. (Department of Agriculture: Perth, W. Aust.)

Mohler C, Frisch JC, Mt. Pleasant J (1997) Evaluation of mechanical weed management programs for corn (*Zea mays*). *Weed Technology* **11**, 123–131.

Mohler CL (1993) A model of the effects of tillage on emergence of weed seedlings. *Ecological Applications* **3**, 53–73. doi: 10.2307/1941792

Mohler CL (2001) Enhancing the competitive ability of crops. In 'Ecological management of agricultural weeds'. (Eds M Liebman, CL Mohler, CP Staver) pp. 270–321. (Cambridge University Press: Cambridge, UK)

Moore CB, Moore JH (2007) HerbiGuide – The Pesticide Expert on a Disk. Version 20.5. Albany, Western Australia, HerbiGuide. Avialable at: www.herbiguide.com.au

Moore JH (2001) Weed control in canola. Final Report for GRDC project DAW552WR.

Mt. Pleasant J, Burt RF, Frisch J (1994) Integrating mechanical and chemical weed management in corn (*Zea mays*). *Weed Technology* **8**, 217–223.

Mulder TA, Doll JD (1993) Integrating reduced herbicide use with mechanical weeding in corn (*Zea mays*). *Weed Technology* **7**, 382–389.

Mulugeta D, Boerboom CM (2000) Critical time of weed removal in glyphosate-resistant *Glycine max*. *Weed Science* **48**, 35–42. doi: 10.1614/0043-1745(2000)048[0035:CTOWRI]2.0.CO;2

Murphy SD, Yakuba Y, Weise SF, Swanton CL (1996) Effect of planting patterns and inter-row cultivation on competition between corn (*Zea mays*) and late emerging weeds. *Weed Science* **44**, 865–870.

Nandula VK, Reddy KN, Duke SO, Poston DH (2005) Glyphosate-resistant weeds: Current status and future outlook. *Outlooks on Pest Management* **16**, 183–187.

Neve PB, Diggle AJ, Smith FP, Powles SB (2003) Simulating evolution of glyphosate resistance in *Lolium rigidum* II: past, present and future glyphosate use in Australian cropping. *Weed Research* **43**, 418–427. doi: 10.1046/j.0043-1737.2003.00356.x

Nordmeyer H (2006) Patchy weed distribution and site-specific weed control in winter cereals. *Precision Agriculture* **7**, 219–231. doi: 10.1007/s11119-006-9015-8

Olsen J, Kristensen L, Weiner J, Griepentrog HW (2005) Increased density and spatial uniformity increase weed suppression by spring wheat. *Weed Research* **45**, 316–321. doi: 10.1111/j.1365-3180.2005. 00456.x

Oriade C, King R, Forcella F, Gunsolus J (1996) A bioeconomic analysis of site-specific management for weed control. *Review of Agricultural Economics* **18**, 523–535. doi: 10.2307/1349587

Osten V, Walker S, Storrie A, Widderick M, Moylan P, Robinson G, Galea K (2007) Survey of weed flora and management relative to cropping practices in the north-eastern grain region of Australia. *Australian Journal of Experimental Agriculture* **47**, 57–70. doi: 10.1071/EA05141

Osten V, Wu H, Walker S, Wright G, Shields A (2006) Weeds and summer crop row spacing studies in Queensland. In 'Papers and Proceedings of the 15th Australian Weeds Conference'. Adelaide, S. Aust. (Eds C Preston, J Watts, N Crossman) pp. 347–350. (Weed Management Society of South Australia, Inc.: Adelaide)

Peek C, Eva N, Carter C, Abrahams M (2006) Maintaining wheat and lupin yields using phase pastures and shielded sprayers to manage increasing herbicide resistance. In 'Crop Updates, Technical Information for Agribusiness'. pp. 50–53. (Department of Agriculture and Food: Perth, W. Aust.)

Peltzer S, Pathan S, Matson PT (2007) Timing of weed removal in wide-row lupins. In 'Crop Updates, Technical Information for Agribusiness'. pp. 72–74. (Department of Agriculture and Food, Western Australia: Perth, W. Aust.)

Peltzer SC, Matson PT (2002) How fast do the seedbanks of five annual cropping weeds deplete in the absence of weed seed input. In 'Proceedings of the 13th Australian Weeds Conference'. Perth, W. Aust. (Eds H Spafford Jacob, J Dodd, JH Moore) pp. 553–555. (Plant Protection Society of Western Australia: Perth, W. Aust.)

Pertoldi C, Topping C (2004) Impact assessment predicted by means of genetic agent-based modeling. *Critical Reviews in Toxicology* **34**, 487–498. doi: 10.1080/10408440490519795

Pester TA, Burnside OC, Orf JH (1999) Increasing crop competitiveness to weeds through crop breeding. *Journal of Crop Production* **2**, 31–58. doi: 10.1300/J144v02n01_04

Powles SB (1986) Appearance of a biotype of the weed *Hordeum glaucum* Steud. resistant to the herbicide paraquat. *Weed Research* **26**, 167–172. doi: 10.1111/j.1365-3180.1986.tb00692.x

Powles SB, Lorraine-Colwill DF, Preston C (1998) Evolved resistance to glyphosate in rigid ryegrass (*Lolium rigidum*) in Australia. *Weed Science* **46**, 604–607.

Powles SB, Preston C (2006) Evolved glyphosate in plants: Biochemical and genetic basis of resistance. *Weed Technology* **20**, 282–289. doi: 10.1614/WT-04-142R.1

Pratley JE, Urwin NAR, Stanton RA, Hohn JA, Krueger RW (1999) Resistance to glyphosate in *Lolium rigidum*. I. Bioevaluation. *Weed Science* **51**, 405–411.

Preston C (2007) Australian glyphosate register: summary and background. National Glyphosate Sustainability Working Group. Available at: www.weeds.crc.org.au/glyphosate

Puckridge DW, Donald CM (1967) Competition among wheat plants sown at a wide range of densities. *Australian Journal of Agricultural Research* **18**, 193–211. doi: 10.1071/AR9670193

Reid D, Aguis P, Buck S, Collin R, Conway M, Keys P, Kuskie J, Spackman G, Sullivan A (2004) Effect of row spacing and plant population on wheat production in central Queensland – 2004. Queensland Department of Primary Industries and Fisheries, Brisbane.

Richter O, Zwerger P, Bottcher U (2002) Modelling spatio-temporal dynamics of herbicide resistance. *Weed Research* **42**, 52–64. doi: 10.1046/j.1365-3180.2002.00262.x

Riethmuller GP (2004) Long-term effects of wheat row spacing and stubble retention on yield, seed quality and ryegrass seed set. In 'CD-ROM of "To Bourke & Back" of the Society for Engineering in Agriculture, Dubbo – Bourke'. Charles Sturt University, Dubbo, NSW, 14–16 September.

Sandison A, Lee V (1998) Wider row spacing reduces canola yields. In 'Highlights of oilseeds research and development in Western Australia'. p. 21. (Agriculture Western Australia: Perth, W. Aust.)

Scursoni JA, Forcella F, Gunsolus J (2007) Weed escapes and delayed weed emergence in glyphosate-resistant soybean. *Crop Protection* **26**, 212–218. doi: 10.1016/j.cropro.2006.04.028

Shaw DR (2005) Remote sensing and site-specific weed management. *Frontiers in Ecology and the Environment* **31**, 526–532.

Siemens MC, Wilkins DE (2006) Effects of residue management methods on no-till drill performance. *Applied Engineering in Agriculture* **22**, 51–60.

Simpfendorfer S, Long R, Coleman B, Shepherd M, Rummery G, Penberthy D, Holmes R, Serafin L, Verrell A, Moore K (2006) On-farm evaluation of inter-row sowing in 2005 to reduce crown rot in winter cereals. In 'Grains Research Update, GRDC'. pp. 51–55, Wagga Wagga (21–22 Feb.); pp. 23–26, Dubbo (23–24 Feb.); pp. 78–81, Goondiwindi (28 Feb.–1 Mar.); pp. 15–18, Mungindi (2 March). (GRDC)

Slattery MG (1998) A study of the balance of tine patterns factors for operating in wheat stubble. In 'International Conference on Engineering in Agriculture'. Perth, W. Aust. p. SEAg 98/044.

Slaughter DC, Chen P, Curley G (1999) Vision guided precision cultivation. *Precision Agriculture* **1**, 199–216. doi: 10.1023/A:1009963924920

Smeda RJ, Schuster CL (2002) Differential sensitivity to glyphosate among biotypes of common waterhemp (*Amaranthus rudis* Sauer). In 'Proceeding of the 13th Australian Weeds Conference'. Perth, W. Aust. (Eds H Spafford Jacob, J Dodd, JH Moore) p. 642. (Plant Protection Society of Western Australia: Perth, W. Aust.)

Storer NP, Peck SL, Gould F, Van Duyn JW, Kennedy GG (2003) Spatial processes in the evolution of resistance in *Helicoverpa zea* (Lepidoptera: Noctuidae) to Bt transgenic corn and cotton in a mixed agroecosystem: a biology-rich stochastic simulation model. *Journal of Economic Entomology* **96**, 156–172.

Storrie A, Cook T, Moylan P, Maguire A, Walker S, Widderick M (2007) 'Managing herbicide resistance in northern NSW.' (Grains Research and Development Corporation: Canberra, ACT)

Storrie AM (2008) Double knocking barnyard grass to manage glyphosate resistance. In 'Grains Research Update. Technology, Management and Profit'. Goondiwindi Community Centre, Goondawindi, NSW.

Swanton CJ, Booth BD, Chandler K, Clements DR, Shrestha A (2006) Management in a modified no-tillage corn–soybean–wheat rotation influences weed population and community dynamics. *Weed Science* **54**, 47–58. doi: 10.1614/WS-05-013R1.1

Taylor I, Charles G (2002) Managing Roundup Ready cotton. In 'WeedPak: a guide for integrated management of weeds in cotton'. (Ed. S Johnson) p. E2.1. (Australian Cotton Cooperative Research Centre: Narrabri, NSW)

Thornby D, Walker SR, Whish PM (2006) Simulating weed persistence and herbicide resistance in the northern grain region using a validated crop growth model with extensions for seedbank dynamics and mating. In 'Managing weeds in a changing climate. Proceeding of the 15th Australian Weeds Conference'. Adelaide, S. Aust. (Eds C Preston, JH Watts, ND Crossman) pp. 499–502. (Weed Management Society of South Australia: Adelaide)

Thorp KR, Tian LF (2004) A review of remote sensing of weeds in agriculture. *Precision Agriculture* **5**, 477–508. doi: 10.1007/s11119-004-5321-1

Tian L, Reid J, Hummel J (1999) Development of a precision sprayer for site-specific weed management. *Transactions of the American Society of Agricultural Engineers* **42**, 893–900.

Timmermann C, Gerhards R, Kuhbauch W (2003) The economic impact of site-specific weed control. *Precision Agriculture* **4**, 249–260. doi: 10.1023/A:1024988022674

Tompkins DK, Fowler DB, Wright AT (1993) Influence of agronomic practices on canopy microclimate and Septoria development in no-till winter wheat produced in the Parkland region of Saskatchewan. *Canadian Journal of Plant Science* **73**, 331–344.

Tredaway-Ducar J, Morgan GD, Wilkerson JB, Hart WE, Hayes RM, Muller TC (2003) Site-specific weed management in corn (*Zea mays*). *Weed Technology* **17**, 711–717. doi: 10.1614/WT02-119

Tull J (1731) 'The new horse-houghing husbandry, or an essay on the principles of tillage and vegetation.' (Aaron Rhames (Dublin): London)

Walker S, Wilson B, Wu H, Widderick M, Taylor I (2006) Weed seed persistence with changing farming practices in southern Queensland. In 'Managing weeds in a changing climate, Proceeding of the 15th Australian Weeds Conference'. Adelaide, S. Aust. (Eds C Preston, JH Watts, ND Crossman) pp. 343–346. (Weed Management Society of South Australia: Adelaide)

Walsh MJ, Owen MJ, Powles SB (2007) Frequency and distribution of herbicide resistance in *Raphanus raphanistrum* populations randomly collected across the Western Australian wheatbelt. *Weed Research* **47**, 542–550. doi: 10.1111/j.1365-3180.2007.00593.x

Wells R (1993) Dynamics of soybean growth in variable planting patterns. *Agronomy Journal* **85**, 44–48.

Whish J, Butler G, Castor M, Cawthray S, Broad I, Carberry P, Hammer G, McLean G, Routley R, Yeates S (2005) Modelling the effects of row configuration on sorghum reliability in north-eastern Australia. *Australian Journal of Agricultural Research* **56**, 11–23. doi: 10.1071/AR04128

Wicks GA, Burnside OC, Felton WL (1995) Mechanical weed management. In 'Handbook of weed management systems'. (Ed. AE Smith) pp. 51–90. (Marcel-Dekker: New York)

Wicks GA, Felton WL, Murison RD, Hanson GE, Nash PG (1998) Efficiency of an optically controlled sprayer for controlling weeds in fallow. *Weed Technology* **12**, 638–645.

Wicks GA, Felton WL, Murison RD, Martin RJ (2000) Changes in fallow weed species in continuous wheat in northern New South Wales, 1981–90. *Australian Journal of Experimental Agriculture* **40**, 831–842.

Widderick M, Walker S, Sindel B (2004) Better management of *Sonchus oleraceus* L. (common sowthistle) based on the weed's ecology. In 'Proceedings of the 14th Australian Weeds Conference'. Wagga Wagga, NSW. (Eds BM Sindel, EN Johnson) pp. 535–537. (Weed Society of New South Wales: NSW)

Wilson JN (2000) Guidance of agricultural vehicles – a historical perspective. *Computers and Electronics in Agriculture* **25**, 3–9. doi: 10.1016/S0168-1699(99)00052-6

Yang CC, Prashar SO, Landry JA, Ramaswamy HS (2003) Development of a herbicide application map using artificial neural network and fuzzy logic. *Agricultural Systems* **76**, 561–574. doi: 10.1016/S0308-521X(01)00106-8

Ye B, Gressel J (1994) Constitutive variation of ascobate peroxidase activity during development parallells that of superoxide dismutase and glutathione reductase in paraquat-resistant *Conyza. Plant Science* **102**, 147–151. doi: 10.1016/0168-9452(94)90032-9

Manuscript received 18 April 2008, accepted 6 March 2009