Chapter 9

The influence of strategically positioned weeds on the yield of chickpea

9.1 Introduction

The relationship between weeds and crops has been examined in many different ways since the time of the first agriculturists. Each weed/crop relationship is unique, and will be dependent on the crop type and density, weed type and density, and the number of weed species present. In recent years, specific studies using empirical models have attempted to mathematically describe what is happening when a single crop competes for resources with a weed at various densities (Cousens 1985a, 1985b). The models derived to explain the relationship between a single weed and a crop do not account for multiple weed species with varying competitive ability (Van Acker *et al.* 1997). A leaf-area model can describe multiple weed competition by the damage coefficients for each weed being combined in an additive fashion (Kropff & Spitters 1991, Van Acker *et al.* 1997). The process of adding weed species does not allow for interactions between weeds increasing or decreasing the competitive ability of the weed burden (Van Acker *et al.* 1997); in practice, the additive approach does not always apply (Haizel & Harper 1973, Blackshaw *et al.* 1987, Hume 1989).

The hyperbolic density curve used at the core of most empirical models describing crop/weed interactions assumes that weeds are dispersed around the crop plant in a uniform pattern (Auld & Tisdell 1988, Brain & Cousens 1990, Wallinga *et al.* 1988). Likewise, weeds sown in most weed research experiments are dispersed evenly within the crop (Brain & Cousens 1990). In practice, weed distribution is dependent on the boundaries of the area under examination and the resolution of the examination within that area. At a low assessment resolution of a small area (e.g. 1 m^2) weeds can appear evenly distributed within the crop. As the resolution and area is increased (e.g. to 1 ha), large areas of crop exist with no weeds and the weedy areas within the crop take on a clumped pattern (Kershaw 1973, Marshall 1988, Rew & Cussans 1995). It can be argued that not all weeds take on a clumped spatial pattern at paddock level; certain infestation levels or types of weed e.g. wind-dispersed weeds may appear to have a random distribution across a paddock. It could also be a function of colonisation time, and species ecology and management. However, Cousens and Mortimer (1995) cite literature showing that the majority of wind-distributed seeds land within a 1.5 m diameter of the parent plant, thus over time, wind-dispersed weeds will form a clumped pattern provided the assessment units are of a suitable resolution.

Auld and Tisdell (1988) using simulated data, suggested that the use of the hyperbolic model on clumped data would significantly over-estimate the yield loss effect on the crop. Brain and Cousens (1990) used experimental data to confirm the assumption that crop yield loss estimates would be over-estimated by the use of calculations that assume a random distribution of weeds. This confirmation also showed that the error between actual clumped data and the assumption of random data in the models was small around the weed threshold (Brain & Cousens 1990).

The use of strategic weed levels or thresholds (the point where the tolerable number of weeds becomes intolerable and some form of weed control is required) can cause confusion when dealing with a sedentary population such as weeds compared with a migratory population such as insects. Threshold assessments in weed populations can be seasonally based (to maintain the current season's yield), (Dunan *et al.* 1995, Berti *et al.* 1996) or based on long-term criteria (reducing weed seed return to the seed bank, thus improving crop yield over time) (Jones & Medd 1997). What makes the two different is the size of the tolerable weed population. At low tolerable weed densities, as observed in a seed bank reduction approach, the over-estimation of yield loss from equations assuming a random distribution is great (Brain & Cousens 1990, Rew *et al.* 1996, Garrett & Dixon 1998).

To determine the error size of yield loss predictions based on random weed dispersal, Brain and Cousens (1990) derived a new empirical model. The general validity of this model could not be empirically tested, because there were very few published estimates of weed frequency distribution (Brain & Cousens 1990, Rew *et al.* 1996). This work, however, highlighted the need for understanding the spatial distribution of weeds and stimulated the idea of targeting weed areas within a crop.

Weeds within a paddock frequently display some degree of clumped or contagious distribution (Kershaw, 1973, Auld & Tisdell 1988). This heterogeneous pattern may be associated with factors that originate from the initial invasion of the site by the weed, and how the dispersal mechanisms of the individual plants interact with the site's macro- and micro-environmental constraints

(Cousens & Woolcock 1997). The mapping of weed patches is one method used to understand the spatial dynamics of weeds (Mortensen *et al.* 1993, Johnson *et al.* 1995, Rew *et al.* 1996). The techniques used to measure weed distribution within a crop are dependent on resolution, the sampling resolution chosen being influenced by the end aim of the map. (e.g. the resolution of the spray system or the cost of creating the map).

The information collected in the production of a weed map can be used in different ways. Firstly, the density of weeds in the major patches can be determined and empirical equations used to calculate the potential yield loss in the weedy areas. Secondly, the co-ordinates of the weed-infested areas can be used to target weed control strategies (Miller *et al.* 1995, Paice *et al.* 1998). Thirdly, maps of the weedy areas can be used to understand the demographics of the individual patches, monitoring their rate of change and spread or their reaction to control strategies over time (Cousens & Woolcock 1997). The development of weed maps has generated interest as a means of reducing the amount and cost of herbicide application. For example, herbicide may be applied to high density weedy areas at one rate, while a reduced rate or no herbicide is applied to low density or weed-free areas (Thompson *et al.* 1991, Johnson *et al.* 1995, Paice *et al.* 1998). The technology required to apply herbicide to weed patches (referred to as patch spraying, spot spraying, or precision spraying) is at the marketable stage (Rew & Cousens 1998).

The development of equipment to spray patches can be divided into two approaches (Nordbo *et al.* 1994): weeds are identified and sprayed in the one application (real time); and weed distribution is assessed over an area then converted to a spray map for subsequent use (mapping). Currently, real-time spraying uses contrasting optical properties of soil, dead plant material and green vegetation to identify plants and spray them (Felton 1995, Felton & Nash 1998). Relying on the optical properties means that there is no distinction between crop and weed, or weed type, so the system is best suited to the application of broad-spectrum herbicides in a fallow situation. The use of real-time spraying in combination with protective shields is also being investigated for use in row crops (Felton pers. comm.). The lack of discrimination between weeds requires these systems to function with broad-spectrum herbicides or suitable tank mixes, which may limit their use for within-crop spraying.

Mapping the spatial distribution of weeds within a paddock has the potential to revolutionise the way herbicides are applied to weeds. Purpose-built spray systems linked to global positioning systems (GPS) and weed maps can apply variable rates of chemicals depending on the degree/level of weed infestation (Miller *et al.* 1995). These systems have been shown to significantly reduce the amount of herbicide applied to the field in densely clumped weed situations (Rew *et al.* 1996, 1997). However, in areas where the weed patches are numerous and small, the reduction of herbicide was minor (Rew *et al.* 1997). These variable rate systems have great potential, but at present the limitation is the ability to produce accurate weed maps in a cost-effective way.

Weed mapping for precision patch spraying has originated from research mapping of weed spatial arrangements. Research maps are usually of high resolution and include density, type, and position information for weeds. The production of high-resolution maps is time consuming and impractical in many farming systems. Rew and Cousens (1998) discuss sampling techniques for mapping weeds and the maximum resolution required for a precision spray system. Thompson *et al.* (1991) reviewed the potential for the development of a real-time weed spray system; within a crop situation, they concluded that any selective spray system would not be based on real time. The inability of optical sensors or geometric measurements of plant parts to distinguish between weed types, or crops and weeds would support the production of weed maps. The development of weed maps over time and at different crop stages could be an added benefit to farmers. Maps could contain an array of information, including: weed patch position; soil types; nutrition; and disturbance. The collection and layering of this information would improve the precision of the spraying procedure and the general management of the paddock.

The production of weed maps can be a tedious operation; however, the monitoring of weeds over time can enable weed management options to be concentrated where they are needed, thus targeting herbicides and effectively reducing the amount of chemical applied and the potential environmental damage. Monitoring the patches over time also improves understanding of weed dispersion and the potential rate of spread (Cousens & Woolcock 1997). Wilson and Brain (1991) reported that over a 10 year period, *Alopecurus myosuroides* Huds. grew in well defined and stable patches in a commercially operated farm. The slow expansion of the *A. myosuroides* may have been a characteristic of this weed, or a result of the 30 x160 m sampling grid used. However, different weeds colonise and expand into new areas in different ways. Two types of weed colonisation and expansion have been discussed in the literature. One type operates by widening the edges of patches in an expanding front ("phalanx spread" adapted from Lovett-Doust 1981). In contrast, the others tactic is "guerrilla spread" where seeds are carried unpredictable distances to new areas causing the development of isolated new patches (Rew & Cussans 1995). Animals are thought to be one of the main vectors for the development of isolated patches in a pasture situation, and machinery has similar effects in a cropping situation (Cousens & Mortimer 1995). The movement of seeds by straight tine, spring tine, or power harrow cultivation forms has been shown to be generally small (84% of seed moved ≤ 1m from the source) with the machinery extending only the edge of the patch along the line of travel (Rew & Cussans 1997). Harvesting has the potential to move seeds much further; however, the majority of seeds will only be moved a small distance from the source (depending on machine speed), but some seed will be trapped and deposited later, a long way from the source (Cousens & Mortimer 1995). The spread of herbicide-resistant wild oat in northern NSW is an example of this; seeds from isolated outbreaks of resistant wild oat occurring in a single paddock were moved by harvesting machinery to neighbouring paddocks (Felton pers. comm.).

The use of real-time decision-supported spray systems has been shown to reduce the amount of herbicide used in a fallow situation by up to 90% (Felton *et al.* 1992, Hanson 1994, Blackshaw 1995). These systems could also successfully spray single weed types in row crops.

The use of shielded spray systems or inter-row cultivation to reduce weeds in row crops will allow weeds to persist in the crop row. The persistence of isolated weeds in a crop row can have a significant economic effect, especially if the crop is of high value (e.g. cotton). Charles *et al.* (1998) described the area of influence of *Datura ferox* and *Xanthium occidentale* plants on cotton to be up to 2 m along the row, while the rows 1 m either side were not affected. This work also showed that a significant yield effect could occur from very low weed densities (1 plant 100 m^{-1} of cotton row). Weed seed dispersion within a patch is dependent on the patch density, but the majority of the seeds would be distributed around the parent plants. This type of distribution would reduce the chance of weeds occurring predominately beside a crop plant, unless the agronomic practices of crop sowing or weed removal encouraged weed development in a specific pattern.

In order to maintain soil structure and reduce soil erosion, no-till farming is being encouraged in the northern grains region of eastern Australia (Martin *et al.* 1988). No-till production causes minimal disturbance of the soil and in so doing can change the occurrence and density of the weed flora (Martin *et al.* 1988). This change in farming methods could affect the spatial pattern of weeds, for example, seeds may emerge mainly within the line disturbed by the sowing tine. To date, work exploring these ideas is unavailable; however, if the sowing practice should influence a weed's pattern of emergence then an understanding of how the proximity of weeds to the crop influences yield loss would be important. If the sowing procedure did stimulate weed emergence in the crop row then moving to wide row sowing while maintaining the same crop density could reduce the weed density across a paddock, because of the reduction in disturbed area.

In Chapter 5, the effect on chickpea yield loss of different weed densities was examined. In these experiments, the weeds were evenly distributed. As stated above, most weeds occur in patches or clumps, when viewed at a paddock resolution. If inter-row cultivation or spraying is used to remove weeds in row crops or if an ordered spatial patterning occurs due to the sowing procedure, weeds may be rearranged in a pattern similar to the crop. The experiment described in this chapter investigated the effect of variable spatial patterns of weeds on the growth and development of chickpea. Weeds were sown within rows, between rows uniformly across plots, or in high-density clumps. In Chapter 8, it was shown that the application of shade at 50% and 80% reduced chickpea yields to levels equivalent to a high-density stand of turnip weed. In this experiment, shade was also applied to areas of a similar size to high-density weed clumps to see if the effect of shade was similar to that of the weed patch.

9.2 Materials and methods

9.2.1 Site

This trial was sown at Tamworth in 1997. Descriptions of the climatic conditions at Tamworth during 1997 are discussed in Chapter 3.

9.2.2 Plant material

The chickpea variety and the wild oat and turnip weed seed used in this trial were the same as those used in Chapter 5.

9.2.3 Sowing

Chickpea seed was sown on 12/6/97 in 64 cm wide rows, and at a rate to achieve a stand of 35 plants m^{-2}. Plots were sown with an 11-tine no-till planter; all tines were engaged but only five tines sowed seed producing five sown wide rows separated by six un-sown tine marks.

Weeds were mixed in dry sand and spread by hand following the chickpea sowing. In-row weeds (IR) were spread along the sown tine furrow; between-row weeds (BR) were spread along the un-sown furrow between each of the sown furrows; and uniform weeds (U) were distributed across the plot as in Chapter 5. Weeds placed in patches were uniformly broadcast across a 1 m wide section of the plot (1P) or two 1m wide sections of plot 2 m apart (2P). The pseudo patches (SP) had shade shelters applied 16 weeks after sowing. Shade shelters consisted of a plastic meshed 30 x 40 cm horticultural seedling tray fixed to a 1 m high stake. Each tray and stake represented a single plant and the number of trays placed in each patch corresponded to the sown weed densities (Plate 9.1). Two densities of weeds were sown for each of these treatments. The weed densities aimed to achieve weed stands of 0, 2 and 8 plants m^{-2} calculated on the entire plot (i.e. a 1 m patch had 8 times the weed density of a uniform plot).

Plate 9.1 Pseudo-weed shade shelters in a patch across a chickpea plot.

Plate 9.2 Surface view of pseudo-weed shade shelters across the chickpea plot.

9.2.4 Experimental design

The experiment was a factorially arranged randomised complete block design, with 3 replicates, two weed densities (2 and 8 plants m^{-2}), two weeds (turnip weed; wild oat), and five weed treatments (weeds placed in crop row (IR); between crop rows (BR); uniformly distributed across the plot (U); uniformly distributed within a 1 m (1P) or 2m (2P) wide section of the plot). Additional treatments that were not part of the factorial were pseudo patches using shade (PP), and a weed-free control). The plots were 8 m long x 3.5 m wide and contained five wide rows and four between row spaces.

9.2.5 Maintenance

Very few broad-leaved weeds occurred in the plots during 1997, and the few that were present were left as a general background weed population. Grass weeds were a problem with two large flushes of *Phalaris paradoxa* occurring. These weeds were controlled in the broad-leaved plots and parts of the wild oat patch plots with fluazifop-p at 106 g a.i. as Fusilade on 13/8/97 and 15/10/97. The separation of wild oat and *Phalaris* from the in-row and between-row treatments was not possible so wild oat plots were a mixture of grass weeds. Removal of grass weeds from the in-row and between-row wild oat treatments was achieved with a narrow shield knapsack sprayer. On all other occasions, herbicide was applied through a hand held 3 m wide boom sprayer, running at 172.4 kPa with an output of 80L ha^{-1}.

9.2.6 Harvest

The chickpea was harvested with a small plot harvester. Three crop rows by an 8 m long section from each plot were harvested (15.36 m^2). Weeds were removed from the 3 crop row and 2 inter-row spaces by hand prior to machine harvesting, and counted and dried in a fan forced hydronic mobile drier at 80°C, circulating air at 10 m^3 sec^{-1} for 48 hours. Following drying and weighing, the turnip weed grain yield was recorded after the samples had passed through a stationary thrasher. Wild oat seed yield was estimated by counting the number of tillers. The machine harvested chickpea grain was also weighed and a 100 seed weight recorded.

9.2.7 Analysis

To enable linear models to be fitted to the density data, the weed densities were logged (log_e) and the control treatments were included as zero density. Hyperbolic models were investigated as a means of describing the crop yield/weed density relationship, but the limited number of data points and the narrow range of the data prevented the use of this model. Linear models were fitted to the yield values and logged weed density data using the REML analysis function of the statistical software package Genstat 5, release 4.1. Standard errors for the predicted results were calculated by the statistical function AS-REML and the models were plotted in S-Plus 4.5.

9.3 Results

The weed densities achieved in each of the treatments were lower than expected (Table 9.1). The low weed emergence, as in Chapter 7, could be explained by the dry conditions in July and August (Fig. 3.3). Turnip weed emergence was higher in the in-row and between-row treatments compared with the uniform and patch treatments, as a result of sowing into the depression left by the press wheels (Table 9.1). The patch treatments were sown with the same number of seeds as for the other treatments and consequently produced a higher density within the patch. Unfortunately, the high density patch was not achieved, because the "so-called high density patches for both wild oats and turnip weed actually had a lower density than did the low density patch. Weed density and dry matter were modelled against the chickpea yields, but the predicted results for these two weed measures were similar, so only the density results are presented. Throughout this Chapter, the wild oat component of the weeds will be referred to as wild oat, despite the fact that it included both wild oat and *Phalaris paradoxa* plants.

Table 9.1 Expected and actual mean weed densities achieved in each of the weed position treatments for wild oat and turnip weed.

Treatment	Turnip weed mean density		Wild oat † mean density	
Weed position	Expected m^{-2}	Actual m^{-2}	Expected m^{-2}	Actual m^{-2}
Between crop rows	2	0.8	2	0.9
	8	2	8	3.0
Within crop rows	2	4.1	2	0.8
	8	2.6	8	2.80
Randomly distributed across the plot	2	1.5	2	0.5
	8	1.8	8	1.6
Single 1 m wide patch per plot	16*	10.2	16*	5.7
	64*	6.5	64*	4.7
Two 1 m wide patches per plot	8*	3.1	8*	2.3
	32*	5.5	32*	5.9
Pseudo patch	0	0	0	0

* *Densities refer to the weed density found within the patch, but equate to the same number of seeds as in the whole plot treatments. Other densities are on a per plot basis.*

† *Wild oat plots included a proportion of Phalaris paradoxa.*

Differences existed between the predicted linear model lines for each treatment (Fig. 9.1). To simplify the figures, the 95% confidence intervals are not shown; however, the shape of the confidence intervals was influenced by the lack of data toward the ends of the fitted lines. If the intervals were included, it would be seen that significant differences existed only in the centres of the predicted lines (the area where the data points are concentrated). The only treatments that showed this type of significant difference were the 1P treatment, the uniform treatment for turnip weed, and the 1P and 2P treatments. The single and double patch treatments consistently yielded more than the other treatments; while the uniform, and between-row and in-row treatments were generally similar.

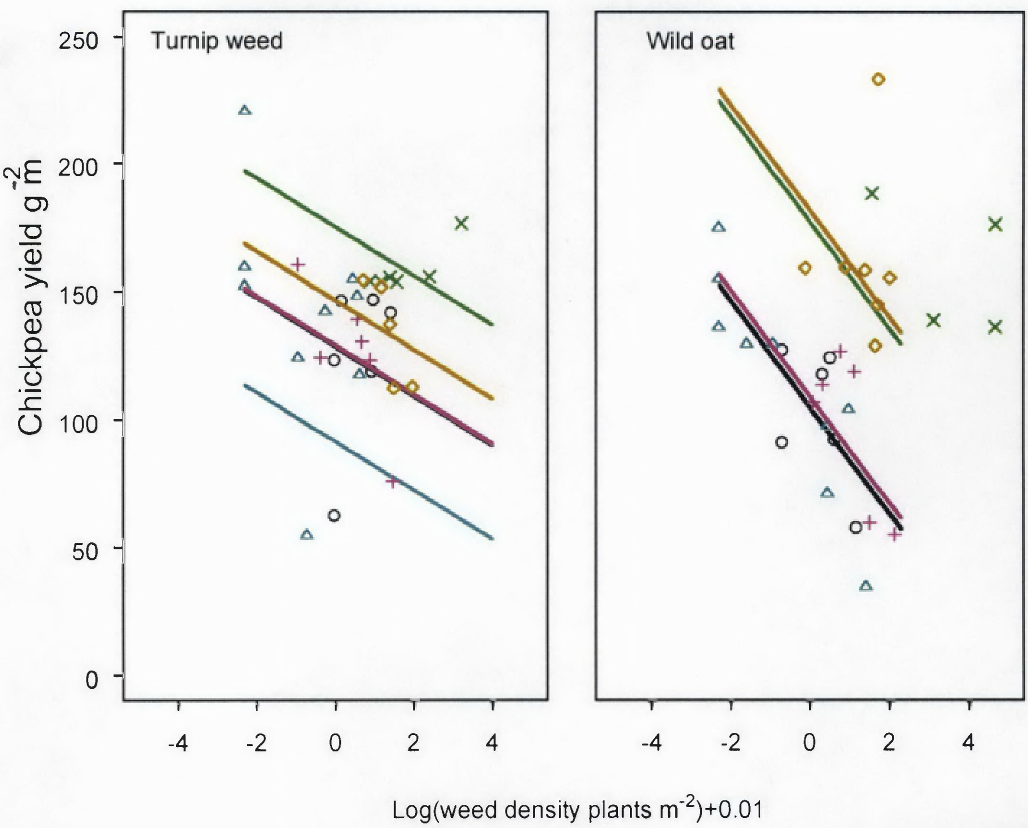

Fig. 9.1 Predicted lines for each weed position treatment showing the relationship between weed density and chickpea yield. Different symbols and colours represent the different weed position treatments: (o) between-row weeds; (+) within-row weeds; (x) weeds distributed in a single 1m patch; (Δ) uniformly distributed weeds; and (✧) weeds distributed in two 1m patches. Wild oat plots included a proportion of Phalaris paradoxa. (Please note the within-row weeds line is superimposed over the between-row line for the turnip weed plot and the between-row weed line is superimposed over the uniformly distributed line in the wild oat plot).

To identify differences between treatments, the predicted yield values calculated at a weed density of 5 plants m^{-2} were compared (Table 9.2). The different weed placement treatments (IR, BR, U) were not significantly different from each other for either turnip weed or wild oats. In the presence of both wild oat or turnip weed, the patch treatments recorded the highest chickpea yields, the single patch being the higher of the two. The turnip weed patch treatments were not significantly different from the three weed placement treatments, but were significantly different ($P < 0.05$) from the pseudo patch treatment.

The wild oat patch treatments were significantly different from the weed placement treatments.

Table 9.2 Table of predicted chickpea yields calculated at five weed plants m^{-2} for each of the strategic weed position treatments for wild oat and turnip weed.

Treatment	Turnip weed	Wild oat †
Weed position	g m^{-2}	g m^{-2}
Between crop rows	113	77
Within crop rows	113	80
Randomly distributed across the plot	118	70
Single 1 m wide patch per plot	159	148
Two 1 m wide patches per plot	131	152
Pseudo patch	76	-
Standard Error	25	20

† *Wild oat plots included a proportion of Phalaris paradoxa.*

9.4 Discussion

There was no difference between the spatial patterning treatments (in-row, between-row, and uniform) of weeds on the chickpea yield for the weed densities investigated in this experiment. The wild oat weed patches had less effect on chickpea yield than these other treatments, supporting the simulations of Auld and Tisdell (1988). A linear model described the relationship (on a log scale) between weed density and chickpea yield. Density hyperbolic models were investigated, but the low density values and the small number of replicates per treatment meant that the linear model gave the best fit. The hyperbolic model could describe the wild oat treatments with higher densities, but for consistency the linear model was used (Fig. 9.1). The higher chickpea yields resulting from the patch treatments were consistent with the relatively small proportion of each plot that was affected by weeds. This was the case for the weed patches (Fig. 9.1); however, the pseudo-patch plots showed a significant chickpea yield reduction. The low actual weed densities achieved in the patch treatments and the high densities of shade shelters used may explain the difference between these two patch treatments; however, the high shade plots would have been expected to have a higher yield than the uniformly distributed weeds. Shade was shown to significantly effect chickpea yield in Chapter 8, and in this case the shade shelters may have had an effect on the whole plot, not just on the intended 1m patch.

The weed densities achieved in this trial were lower than intended (Table 9.1) and may be a reason why the treatments were not significantly different; a second reason would be the narrow range of densities limiting the ability of the model to describe the variation. A second year of experiments was established in 1998 to compare with the results of 1997. The 1998 experiments repeated the weed position treatments described above with a wider range of weed densities, and a second experiment aimed to identify if weed spatial position is influenced by the sowing procedure in no-till farming systems. Unfortunately, due to above average rainfall, flooding and disease in 1998, both additional trials had to be abandoned.

Assuming that the sowing procedure in no-till systems does not influence the spatial pattern of weeds, then the use of wide rows and between-row weed control would significantly reduce weed populations within the weedy areas in chickpea crops. Inter-row weed control would leave weeds in the crop rows, but the overall weed density would be reduced. Inter-row weed spraying may have to use a broad-spectrum herbicide and protective shields for the crop. To remove weeds from the crop row a selective herbicide may be required. The application of a selective herbicide to weed areas in a row crop could be directed by a previously obtained weed map; or via real-time spraying system which use either image processing, or reflectance technology to identify the weeds (Felton & Nash 1998, Robbins, 1998). If image-processing technology were used to identify broad-leaved weeds in a cereal crop or grass weeds in pulse crops, a degree of real-time specific weed spraying could occur. Thompson *et al.* (1991) concluded that a selective spray system would not be based on real-time technology, and Nordbo *et al.* (1994) described real-time and mapping as two separate approaches to weed patch spraying. The advances in current technology mean that these two forms of patch spraying do not need to be separate, and selective real-time spray systems could be combined with previously made weed maps to maximise the success of herbicide applications. This approach may also help reduce the number of times spray rigs pass over a crop. A final advancement in these forms of technology would be to use the real-time spray systems to prepare weed maps for the future.

Chickpeas are suited to production on wide rows in the northern grains region (Chapter 5) and the use of wide rows should allow the inter-row space to be weeded by real-time shielded spray systems (Felton pers. comm.).

The results of this Chapter show that in this case weeds in and between the crop row cause the same degree of crop loss. This knowledge and the use of wide rows for chickpea production combined with inter-row weeding would maximise the land area, which can be easily weeded, and improve yield. However, if wide rows and inter-row weeding were combined with high resolution weed maps, reflectance sensors, image processing real-time spray systems, and selective herbicides, even greater weed control could be achieved with less herbicide applied.

Chapter 10

Conclusions

10.1 Introduction

Weeds are a major limitation to the production of chickpea in the northern grains region of eastern Australia, because of the limited number of herbicides for the control of broad-leaved weeds and potential for resistance to the available grass control herbicides. The foundations of an integrated weed management system for chickpea require a basic understanding of how weeds interact with chickpea. To achieve this, a series of research objectives were set including the quantification of competitive effects of weeds on chickpea, the establishment of a sound basis for the timing of weed control and the identification of cultural management practices and breeding objectives for chickpea which increases its competitive ability. A range of experiments was conducted to achieve these goals. This chapter, draws attention to the major findings from the completed experiments with respect to these aims, and discusses directions for potential research.

10.2 Quantification of competitive effects of weeds on chickpea

The relative growth rates of chickpea, turnip weed (*Rapistrum rugosum*) and wild oat (*Avena sterilis* subsp. *ludoviciana*) were examined to investigate their competitive interactions. The results from this single year experiment completed at two sites showed that chickpea, turnip weed and wild oat had similar growth curves. Rapid growth of all plants commenced around 450 degree-days after sowing and produced a classical growth curve (Fig. 7.5 and 7.7). When chickpea was grown in the presence of turnip weed or wild oat the curve shape changed. The point where the values predicted by the curves (weedy and weed-free) differ significantly was defined as the point of observed competition (The observed point of competition is the point were reduced growth in the weedy chickpea crop can be measured. It is not the point that competition occurs) and, in the case of turnip weed, this separation is significant at 1100 degree-days after sowing (Fig. 7.5). Having these data means that for different regions, based on a sowing date of mid May, the 800-1100 degree days can be calculated and control options implemented well before this time. This approach would be improved by the combination of degree-days and photoperiod such as in the crop development modelling tool DEVEL (Holzworth & Hammer 1992).

Different densities of weeds were shown to affect the yield of chickpea in a predictable manner. A rectangular hyperbolic curve described the effect of increasing weed density on chickpea yield loss. The curve showed that relatively low densities of turnip weed (8 plants m^{-2}) or wild oat (10 plants m^{-2}) growing throughout the life of the crop could reduce the chickpea grain yield by 50%. This information will help predict potential yield losses and decisions for weed control.

The location of the weeds within the crop, i.e. growing in the crop row, between the crop rows, or randomly dispersed through the crop, did not affect yield loss (Fig. 9.1); however, poor emergence reduced the weed density in this trial. High-density patches within the chickpea crop did not reduce chickpea yield to the same extent as distributing the same number of weeds uniformly throughout the whole chickpea plot (Table 9.2). These two results have implications for management practices that rely on predictive models, because the weed distribution within the crop, if not considered, can significantly bias results.

To assist in the management of weeds in chickpea, predictive models based on relative leaf-area were investigated to help estimate the effect of specific weed infestations on chickpea yield early in the season. Relative leaf-area was selected as a modelling parameter because of its non-destructive nature, and its potential for incorporation into a practical mechanised system for routine use. The 1-parameter leaf area model (Equation 6.1) offered the most robust predictions from the data collected. Weed density was not used to predict yield loss due to unfavourable reports within the literature, relating to the problem of assigning equal damage coefficients to very small and large weeds. However, examination of the chickpea and weed (wild oat and turnip weed) growth curves (Figs 7.5 to 7.8) suggests that density may be suitable for yield loss prediction, because the synchronous flush of weed growth may cause early- and late-emerging weeds to elongate together, and compete similarly against the crop.

10.3 Establishment of a sound basis for the timing of weed control

The relative crop and weed growth curves (Chapter 7) highlighted suitable times, based on number of degree-days, for controlling weeds in chickpea. The optimum time of around 500 degree-days after sowing was the same at both the experimental sites, and was determined by maximising chickpea yields as well as minimising weed seed returns to the seed bank. This timing was considerably later than what may have been deduced intuitively and resulted from slow initial growth rates of the weeds (turnip weed and wild oat) and chickpea.

10.4 Identification of cultural management practices and breeding objectives for chickpea which increase its competitive ability

Decreasing the distance between crop rows is often seen as a way of improving crop competitive ability, because narrow row spacing reduces the time to full canopy closure. Conversely, producing chickpea on wide rows has some benefits. The wider rows increase airflow between the plants, reduce disease, and allow cereal stubble to remain undisturbed which helps prevent erosion. On the other hand, increasing row widths may promote weed growth by increasing the time to crop canopy closure. This research showed that increasing the row spacing from 32 to 64 cm had no detrimental effect on the yield of chickpea when grown in the presence of wild oats or turnip weed. The weed density response curves in the narrow and wide rows showed a positive effect on yield by the use of wide rows in one case, but for the remainder there was no significant difference, reinforcing that wide row spacings did not reduce the competitive ability of chickpea. The positive effect of wide rows may have been due to better disease control in these rows. The use of wide rows would also benefit additional weed control methods that could be applied to the between row space during crop production.

Several different chickpea varieties and breeding lines are available in Australia. Some of these were shown to differ in their competitive ability, but they were all considerably less competitive than wheat and canola. Current breeding objectives of improving plant height and vigour are leading to small improvements in competitive ability of new chickpea varieties. If a variety of chickpea could be developed with radically different plant architecture e.g. greater height and denser canopy, then this would strengthen the competitive ability of the crop. For added benefits, such a variety would also require a growth curve with a shorter lag phase in the early stages, thus enabling it to reach its mature height faster and shade the weeds earlier in the season.

10.5 Future research directions

The main areas arising from this program that would benefit from further investigation are the effects of the time of weed removal, the interactions between other weeds of varying importance and chickpea, and the effect of location and therefore climate and photoperiod on chickpea and weed growth.

The "time of weed removal" results obtained in this study showed particular promise and suggests that this factor has potential for improving chickpea weed management. However, only one season's data from two sites was used to create the growth curves on which this method is based, so their reliability needs to be tested with repeated experiments under different environmental conditions, and using a range of weed species.

The effect of weed density is an important criterion in understanding crop/weed interactions. This study focused on turnip weed and wild oat, but a range of other weeds occur in northern chickpea crops. Weeds such as sowthistle (*Sonchus oleraceus*), bindweed (*Fallopia* spp.), paradoxa grass (*Phalaris paradoxa*), and deadnettle (*Lamium amplexicaule*) can occur in chickpea, but nothing is known of their competitive effect on the crop or how combinations of these weeds interact to reduce crop yield. An understanding of the relative damage imposed by these secondary weeds would help grain growers give priorities to weeds and decide on control strategies, since the removal of specific weeds may be more important than creating a weed-free crop: if so it would have the added advantage reducing herbicide use and production costs. Economic modelling, simulation modelling, decision support systems, and precision weed management systems all require a good understanding of weed/crop interactions, and their effectiveness in any integrated weed management system is dependent on the quality and diversity of these interaction data.

10.5.3 Environmental effects

The relationships between the environment, the crop, and the weed community are vital in understanding how a cropping system works. While this research has focused on two sites, future experiments, as outlined above, should involve the collection of detailed climatic information to enable comprehensive simulation models to be developed. Simulation models require considerable input, but their use in predicting outcomes (yield loss, economic returns, relative growth rates of weeds and crops, weed seed production) and identifying gaps in current knowledge are invaluable.

Other research areas, such as precision weed management and economic modelling, are worthy of investigation but, without a thorough understanding of the competitive effects of different weeds on chickpea and the effects of the timing of weed control, they are likely to be ineffectual.

This research has identified some factors that can be combined to help improve chickpea weed management:

- Increased use of post-emergence spray applications
- Reduced reliance on pre-emergence herbicides
- Use of in-row spot spraying and shielded spray systems
- Strategic applications of herbicide

As part of an integrated weed management package, this work provides detailed information on crop/weed interactions and identifies strategic times for applying weed control, to help reduce the need for repeated herbicide application. These are some of the important factors involved in improving chickpea weed management. It is hoped that integrated weed management of chickpeas will be dynamic through a continually evolving weed management system to ensure better chickpea production.

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Appendix

Table A.1. Predicted values for the parametric and non-parametric models at Times 1 and 2, 1996. 1P, 2P, and NP refer to the 1-parameter, 2-parameter, and non-parametric models, respectively. Results are the fractional yield loss and values in brackets are the standard errors.

	SITE	TAMWORTH						WARIALDA					
		TIME 1			TIME 2			TIME 1			TIME 2		
	Cover	1P	2P	NP	1P	2P	NP	1P	2P	NP	1P	2P	NP
Turnip	0.1	0.25	0.37	0.32	0.11	0.12	0.15	0.20	0.24	0.25	0.24	0.52	0.27
weed		(±0.1)	(±0.1)	(±0.1)	(±0.02)	(±0.03)	(±0.04)	(±0.02)	(±0.1)	(±0.1)	(±0.03)	(±0.03)	(±0.03)
	0.2	0.43	0.46	0.37	0.22	0.24	0.25	0.29	0.37	0.32	0.41	0.55	0.38
		(±0.1)	(±0.1)	(±0.1)	(±0.03)	(±0.05)	(±0.04)	(±0.04)	(±0.1)	(±0.04)	(±0.04)	(±0.03)	(±0.03)
	0.3	0.56	0.50	0.42	0.33	0.35	0.34	0.41	0.46	0.39	0.55	0.55	0.48
		(±0.1)	(±0.1)	(±0.1)	(±0.04)	(±0.05)	(±0.03)	(±0.04)	(±0.04)	(±0.03)	(±0.04)	(±0.03)	(±0.03)
	0.4	0.66	0.52	0.48	0.44	0.45	0.43	0.52	0.52	0.47	0.65	0.56	0.59
		(±0.1)	(±0.7)	(±0.1)	(±0.05)	(±0.05)	(±0.03)	(±0.04)	(±0.03)	(±0.03)	(±0.04)	(±0.03)	(±0.03)
	0.5	0.74	0.54	0.53	0.54	0.54	0.52	0.62	0.56	0.54	0.74	0.56	0.70
		(±0.1)	(±0.1)	(±0.1)	(±0.05)	(±0.04)	(±0.03)	(±0.04)	(±0.04)	(±0.04)	(±0.03)	(±0.03)	(±0.04)
	0.6	0.81	0.55	0.58	0.64	0.63	0.62	0.71	0.59	0.62	0.81	0.56	0.80
		(±0.1)	(±0.1)	(±0.10)	(±0.04)	(±0.04)	(±0.04)	(±0.04)	(±0.1)	(±0.1	(±0.02)	(±0.03)	(±0.06)
	0.7	0.87	0.55	0.63	0.73	0.71	0.71	0.79	0.62	0.69	0.87	0.56	0.91
		(±0.03)	(±0.1)	(±0.1)	(±0.03)	(±0.05)	(±0.05)	(±0.03)	(±0.1)	(±0.1)	(±0.02)	(±0.03)	(±0.07)
	0.8	0.92	0.56	0.68	0.82	0.78	0.80	0.87	0.64	0.77	0.92	0.56	1.02
		(±0.02)	(±0.1)	(±0.1)	(±0.03)	(±0.08)	(±0.06)	(±0.02)	(±0.1)	(±0.1)	(±0.02)	(±0.03)	(±0.09)
Wild	0.1	0.22	0.30	0.28	0.09	0.10	0.12	0.22	0.36	0.33	0.26	0.58	0.33
oat		(±0.04)	(±0.1)	(±0.1)	(±0.02)	(±0.03)	(±0.05)	(±0.03)	(±0.01)	(±0.1)	(±0.04)	(±0.04)	(±0.03)
	0.2	0.40	0.43	0.36	0.18	0.20	0.20	0.39	0.47	0.41	0.44	0.60	0.41
		(±0.1)	(±0.1)	(±0.04)	(±0.03)	(±0.05)	(±0.04)	(±0.05)	(±0.04)	(±0.04)	(±0.05)	(±0.03)	(±0.03)
	0.3	0.53	0.50	0.44	0.28	0.30	0.29	0.52	0.53	0.48	0.58	0.60	0.49
		(±0.1)	(±0.1)	(±0.5)	(±0.04)	(±0.05)	(±0.04)	(±0.05)	(±0.04)	(±0.04)	(±0.05)	(±0.04)	(±0.03)
	0.4	0.64	0.55	0.52	0.37	0.39	0.38	0.63	0.56	0.55	0.68	0.60	0.57
		(±0.1)	(±0.1)	(±0.7)	(±0.05)	(±0.05)	(±0.03)	(±0.05)	(±0.1)	(±0.1)	(±0.05)	(±0.04)	(±0.03)
	0.5	0.73	0.58	0.60	0.47	0.48	0.47	0.72	0.58	0.63	0.76	0.61	0.66
		(±0.1)	(±0.1)	(±0.9)	(±0.05)	(±0.05)	(±0.04)	(±0.04)	(±0.1)	(±0.1)	(±0.04)	(±0.04)	(±0.04)
	0.6	0.80	0.60	0.67	0.57	0.56	0.55	0.79	0.60	0.70	0.83	0.61	0.74
		(±0.04)	(±0.1)	(±0.1)	(±0.05)	(±0.05)	(±0.05)	(±0.04)	(±0.1)	(±0.1)	(±0.03)	(±0.04)	(±0.05)
	0.7	0.86	0.62	0.75	0.67	0.64	0.64	0.85	0.61	0.77	0.88	0.61	0.82
		(±0.03)	(±0.1)	(±0.1)	(±0.05)	(±0.1)	(±0.06)	(±0.03)	(±0.1)	(±0.1)	(±0.02)	(±0.04)	(±0.06)
	0.8	0.91	0.64	0.83	0.78	0.71	0.73	0.91	0.62	0.84	0.92	0.61	0.90
		(±0.02)	(±0.1)	(±0.2)	(±0.04)	(±0.1)	(±0.07)	(±0.02)	(±0.1)	(±0.1)	(±0.01)	(±0.04)	(±0.07)

Table A.2 Predicted values for the parametric and non-parametric models at the four times of assessment. 1P, 2P, and NP refer to the 1-parameter, 2-parameter, and non-parametric models respectively. Results are the fractional yield loss and standard errors are given in brackets.

	1997	TIME 1			TIME 2			TIME 3			TIME 4		
Site	Cover	1P	2P	NP	1P	2P	NP	1P	2P	NP	1P	2P	NP
Tamworth	0.1	0.25	-	0.26	0.44	0.45	0.38	0.08	0.26	0.18	0.003	0.11	0.11
		(±0.08)		(±0.04)	(±0.06)	(±0.07)	(±0.05)	(±0.06)	(±0.02)	(±0.02)	(±0.00)	(±0.05)	(±0.02)
	0.2	0.43	-	0.34	0.64	0.51	0.63	0.33	0.18	0.24	0.007	0.18	0.14
		(±0.1)		(±0.09)	(±0.06)	(±0.12)	(±0.11)	(±0.04)	(±0.04)	(±0.02)	(±0.00)	(±0.06)	(±0.02)
	0.3	0.57	-	0.43	0.76	0.55	0.88	0.35	0.27	0.30	0.01	0.23	0.17
		(±0.1)		(±0.4)	(±0.05)	(±0.16)	(±0.17)	(±0.05)	(±0.05)	(±0.03)	(±0.01)	(±0.05)	(±0.02)
	0.4	0.67	-	0.52	0.83	0.58	1.13	0.38	0.36	0.37	0.02	0.26	0.20
		(±0.09)		(±0.19)	(±0.04)	(±0.18)	(±0.23)	(±0.05)	(±0.06)	(±0.03)	(±0.01)	(±0.04)	(±0.02)
	0.5	0.75	-	0.61	0.88	0.59	1.38	0.38	0.46	0.43	0.03	0.29	0.23
		(±0.08)		(±0.24)	(±0.03)	(±0.20)	(±0.29)	(±0.06)	(±0.06)	(±0.04)	(±0.01)	(±0.04)	(±0.02)
	0.6	0.82	-	0.69	0.92	0.60	1.64	0.39	0.56	0.49	0.04	0.31	0.26
		(±0.06)		(±0.29)	(±0.02)	(±0.21)	(±0.35)	(±0.06)	(±0.06)	(±0.05)	(±0.02)	(±0.03)	(±0.02)
	0.7	0.88	-	0.78	0.94	0.61	1.89	0.39	0.66	0.56	0.07	0.33	0.30
		(±0.05)		(±0.34)	(±0.01)	(±0.22)	(±0.41)	(±0.07)	(±0.06)	(±0.07)	(±0.03)	(±0.03)	(±0.03)
	0.8	0.92	-	0.87	0.97	0.62	2.14	0.40	0.77	0.62	0.11	0.34	0.33
		(±0.03)		(±0.39)	(±0.01)	(±0.22)	(±0.47)	(±0.07)	(±0.04)	(±0.08)	(±0.04)	(±0.03)	(±0.03)
Warialda	0.1	0.26	0.26	0.23	0.06	0.07	0.12	0.23	0.25	0.21	0.02	0.05	0.09
		(±0.05)	(±0.05)	(±0.04)	(±0.03)	(±0.04)	(±0.04)	(±0.02)	(±0.02)	(±0.02)	(±0.00)	(±0.02)	(±0.02)
	0.2	0.44	0.27	0.31	0.13	0.15	0.17	0.41	0.41	0.36	0.05	0.11	0.14
		(±0.06)	(±0.06)	(±0.1)	(±0.02)	(±0.04)	(±0.03)	(±0.03)	(±0.02)	(±0.02)	(±0.01)	(±0.03)	(±0.02)
	0.3	0.57	0.28	0.40	0.20	0.21	0.21	0.54	0.51	0.50	0.17	0.17	0.19
		(±0.07)	(±0.06)	(±0.2)	(±0.04)	(±0.04)	(±0.03)	(±0.03)	(±0.03)	(±0.03)	(±0.03)	(±0.03)	(±0.02)
	0.4	0.68	0.28	0.48	0.30	0.37	0.26	0.65	0.59	0.64	0.22	0.22	0.24
		(±0.06)	(±0.07)	(±0.2)	(±0.05)	(±0.04)	(±0.04)	(±0.02)	(±0.04)	(±0.04)	(±0.03)	(±0.03)	(±0.02)
	0.5	0.76	0.29	0.57	0.36	0.32	0.30	0.73	0.64	0.79	0.28	0.28	0.29
		(±0.05)	(±0.07)	(±0.3)	(±0.05)	(±0.08)	(±0.06)	(±0.02)	(±0.06)	(±0.05)	(±0.03)	(±0.03)	(±0.02)
	0.6	0.83	0.29	0.65	0.46	0.37	0.35	0.81	0.70	0.93	0.33	0.33	0.33
		(±0.04)	(±0.07)	(±0.4)	(±0.06)	(±0.12)	(±0.08)	(±0.02)	(±0.07)	(±0.06)	(±0.03)	(±0.03)	(±0.02)
	0.7	0.88	0.29	0.74	0.57	0.42	0.39	0.87	0.72	1.07	0.39	0.39	0.38
		(±0.03)	(±0.08)	(±0.4)	(±0.06)	(±0.17)	(±0.10)	(±0.01)	(±0.08)	(±0.07)	(±0.03)	(±0.03)	(±0.03)
	0.8	0.92	0.29	0.82	0.70	0.46	0.44	0.92	0.75	1.22	0.44	0.44	0.44
		(±0.02)	(±0.08)	(±0.5)	(±0.05)	(±0.23)	(±0.12)	(±0.01)	(±0.10)	(±0.09)	(±0.03)	(±0.03)	(±0.04)