

**Factors affecting seedbank dynamics
of *Lolium rigidum* Gaudin and other
cropping weeds of northern NSW**

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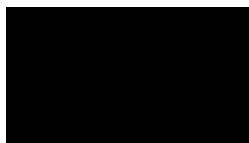
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Declaration

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being for any other degrees or qualifications.

I certify that any help received in preparing the thesis, and all sources used, have been acknowledged in this thesis.



Sandeep Narwal

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Abstract

Annual ryegrass (*Lolium rigidum* Gaudin) is one of the most important weeds of the grain cropping regions of southern Australia. The over reliance on herbicides with similar modes of action has resulted in the evolution of herbicide resistance in many *L. rigidum* populations. Recently, glyphosate-resistant *L. rigidum* was discovered on the Liverpool Plains near Tamworth in northern NSW. Little published work exists on the current status of the size and composition of glyphosate resistant *L. rigidum* seedbanks and other weeds identified as at risk of developing resistance on the Liverpool Plains. Also, there is little information available about the factors affecting dormancy and viability of *L. rigidum* seeds or the effects of modified management (alternative tillage and burning) options on glyphosate resistant *L. rigidum* seedbank dynamics, particularly in the northern grain region.

The extent of resistance in *L. rigidum* seed collected from the Liverpool Plains was evaluated against a range of herbicides, including glyphosate, in a glasshouse experiment in 2005 and repeated in 2006. Another commercial seed lot originating from Victoria and presumed to be susceptible to glyphosate was purchased locally for comparison with the glyphosate resistant seed lot. Both populations had cross resistance to group A herbicides (diclofop-methyl and tralkoxydim) as well as multiple resistance to group B (chlorsulfuron) and M (glyphosate) herbicides. Sulfometuron provided substantial control of *L. rigidum* collected from the Liverpool Plains but not from the Victorian populations.

Characterisation and monitoring of *L. rigidum* and other weed species seedbanks was undertaken for three consecutive years from 2004 to 2006 on the Liverpool Plains. Four properties (sites) were selected for sampling and either 3 or 4 paddocks were sampled from each site where *L. rigidum* was known to occur. The seedbank species remained unchanged over the 3 years under the management systems employed. Greatest *L. rigidum* numbers were found in the top 0-2 cm of soil which may affect their longevity and seed emergence patterns. At most of the properties, farmers adopted strategies such as alternate use of herbicides to restrict the *L. rigidum* seedbank numbers to low levels. *Polygonum aviculare* and *Sonchus oleraceus* with variable numbers across properties stand at risk of acquiring resistance to herbicides and so need to be controlled with alternative methods. *Crassula colorata* and *Lamium amplexicaule* numbers, although not in the high risk list, are still there in numbers that pose a threat of increasing populations if not treated.

Factors affecting seed longevity and emergence of *L. rigidum* seedlings were examined under polyhouse conditions and as indicated by the monitoring work above, seeds either with summer or winter dominant rainfall lost all viability after 16 months of burial. Maximum emergence in the polyhouse occurred in mid autumn within the 18 to 20°C maximum temperature range. Longevity of *L. rigidum* seeds was also tested under field conditions at Tamworth and found to be restricted to within 15 months of burial whether at 0, 5 or 10 cm depth. Seeds germinated quickly with rainfall received soon after sowing and lost more than 90% dormancy within the first 6 months of burial.

The WEEDM model was assessed for its potential application in northern New South Wales. Emergence patterns of seed of *L. rigidum* from two sources, including a population from the Liverpool Plains, with cultivation and seed burial, were compared with the predicted emergence by a WEEDM in a no-till situation. The *L. rigidum* emergence predictions by this model are likely to be reasonably accurate for no-till situations in the northern grain region but the model is not calibrated to predict emergence under cultivated or ploughed field conditions, which is a limitation of the program if more farmers begin to again cultivate judiciously to control herbicide resistant weeds.

Three field experiments were conducted over 2 years to examine the value of alternative tillage and burning treatments on weed emergence and the soil seed bank of *L. rigidum* and other prominent weeds from the northern grains region. One year of stubble burning with chisel ploughing (SBC) and mould board ploughing (MBP) alone provided substantial control of *L. rigidum*, *Avena fatua*, *Hibiscus trionum* and *Phalaris paradoxa*. *Lolium rigidum* was found to have low dormancy and longevity in the cropped situations which should enable farmers to exhaust the seedbanks within 2 years. *Polygonum aviculare*, *L. amplexicaule* and *Melilotus indica* responded best to MBP, while *P. paradoxa* had greatest reductions with SBC. Alternative management strategies to herbicides helped in decreasing or at least restricting the seedbanks of *L. rigidum* and other important weeds.

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Chapter 1. Introduction

1.1. Project overview

Cropping systems in Australia over the last 30 years have largely become dependent on herbicides for weed control. The appearance of herbicide resistant weed populations is an increasing problem in sustaining the productivity of these cropping systems. New alternative herbicides have improved the situation but their use must be carefully targeted. Farmers in other countries have also found similar problems of resistant biotypes caused by repeated long term use of herbicides.

Annual ryegrass (*Lolium rigidum* Gaudin) is one of the most important weeds of the grain cropping regions of southern Australia (Western Australia, South Australia, Victoria, and New South Wales)(Pannell *et al.* 2004). The over reliance on herbicides with similar modes of action has resulted in the evolution of herbicide resistance in many *L. rigidum* populations (Gill 1995, Llewellyn and Powles 2001). Recently, glyphosate-resistant *L. rigidum* was discovered on the Liverpool Plains near Tamworth in northern NSW (Andrew Storrie, NSW DPI, pers. comm.). Risk analysis done by Walker *et al.* (2004) in Australia's northern grain belt identified a number of common weeds with a moderate to high risk of glyphosate resistance in addition to *L. rigidum*. This level of risk is due to the high frequency of glyphosate use on these weeds in fallows, little rotation with herbicides with other modes of action or with other weed control options, and high levels of infestation.

While herbicide resistance has been much slower to develop in the northern grain region of Australia, due largely to summer cropping options, resistance is now appearing and farmers are contemplating alternative methods to control weeds. Such practices include the tillage system used, alternative crop rotations and other cultural controls such as burning. All these options can lead to a decrease in weed seed banks in the soil which are the main source of ongoing weed infestations (Marks and Mohler 1985a). Similarly, the soil seedbank is also an indicator of past and present weed populations and reflects the cumulative effects of many years of crop and soil management (Cardina *et al.* 1991, Clements *et al.* 1996).

There is a need to better understand aspects of the ecology of *L. rigidum* in the northern grain region before further alternative approaches for the control of *L. rigidum* can be

recommended. Relatively little is known about the dormancy and viability of *L. rigidum* seeds in this environment (and the factors affecting survival) or the effects of modified management (alternative tillage and burning) options on glyphosate resistant *L. rigidum* seedbank dynamics. The current status of the size and composition of glyphosate resistant *L. rigidum* seedbanks and other weeds identified as at risk of developing resistance on the Liverpool Plains of northern NSW are also unknown. For an effective understanding of the above issues, there is also a need to evaluate the level of resistance occurring in different *L. rigidum* populations against widely used herbicides. Additionally, there is a need to understand the factors influencing the survival and viability of *L. rigidum* seeds under varying soil, rainfall and depth conditions. This thesis is an effort to address this current gap in weed ecological studies for *L. rigidum*.

1.2. General aims

The aims of the research were to:

- evaluate resistance in *L. rigidum* to herbicides;
- characterise and monitor the weed seedbanks on the Liverpool Plains of northern NSW using selected field locations;
- determine the viability and dormancy of *L. rigidum* seeds as affected by a range of soil and environmental factors;
- correlate seedling emergence of *L. rigidum* with the WEEDEM model; and
- identify management strategies for control of *L. rigidum* and other weeds.

1.3. Format of thesis

There are eight chapters in the thesis. They include an introduction, a review of literature, the experimental chapters comprised of aims and methods followed by analysis of results and discussion, and final conclusions.

1.4. Publications

A list of publications arising from this thesis is located in the appendix.

Chapter 2. Review of literature

2.1. Introduction

An understanding of the dynamics of seed banks is widely recognised as being important for effective of weeds. Lack of knowledge of seed bank changes specifically for weeds like glyphosate resistant annual ryegrass (*Lolium rigidum*) is the driving force for conducting seed bank oriented research. This review of literature will examine the available information on seedbanks across various climatic and edaphic environments that specifically relates to the objectives of this thesis. The review will concentrate on *L. rigidum* and other similar problem weeds, whether herbicide resistant or non resistant. The sections of this review are:

- 2.1 introduction;
- 2.2 evaluation of resistance in *L. rigidum* to herbicides;
- 2.3 seedbank size and composition;
- 2.4 longevity/viability of seeds of *L. rigidum* and other weeds;
- 2.5 correlating seedling emergence with WEEDEM;
- 2.6 management of *L. rigidum* and other weeds; and
- 2.7 conclusions.

2.2. Evaluation of resistance in *L. rigidum* to herbicides

Glyphosate was introduced into Australia in 1976 and was rapidly and enthusiastically adopted by growers (Neve *et al.* 2002). It is a major non-selective herbicide used to control weeds in many situations including fallows and pre-seeding. Burgeoning resistance to postemergence selective herbicides and the increased adoption of reduced tillage seeding operations has further aggravated the use and utility of glyphosate in broadacre cropping Australia-wide. Despite widespread, frequent and repeated applications, the first confirmed case of glyphosate resistance in *L. rigidum* was not reported until 1996. In Australia, resistance to glyphosate in *L. rigidum* was first reported in 1996 (Pratley *et al.* 1996). Since then, cases have been reported in every grain producing state in Australia and in other agroecosystems. Besides glyphosate, several other herbicides belonging to groups A and B have also been found ineffective in controlling *L. rigidum* populations due to resistance. Evaluation of herbicide resistance is an important tool to judge the ongoing levels of resistance against particular herbicides and also to know the biotypes which are under

threat of acquiring resistance. All the herbicide rates mentioned are of active ingredients unless otherwise specified.

Western Australia

In 2001, the first case of glyphosate resistant *L. rigidum* in Western Australia (WA) was confirmed. Individuals from this population, collected from the northern wheatbelt of W.A (Neve *et al.* 2002) survived 735 g ha⁻¹ of glyphosate in the field. A glyphosate dose of 510 g ha⁻¹ controlled 95 to 100% plants of the Susceptible (S) biotypes of *L. rigidum* collected from paddocks of farmers in Western Australia. The other plants which did not die apparently were severely affected and did not produce seeds. In contrast, 48 to 86% of the F2 plants of the Resistant (R) biotypes survived 510 g ha⁻¹ and 23 to 37% survived 1020 g ha⁻¹ clearly establishing that these populations are resistant to glyphosate (Hashem *et al.* 2003).

Ninety percent of Western Australian grain growers had some herbicide resistance on their property out of 121 surveyed (Owen *et al.* 2002). Walsh *et al.* performed similar evaluation trials with *Raphanus raphanistrum* (wild radish) and found that very high frequencies of wild radish populations are resistant to the group B herbicide chlorsulfuron. Wild radish populations resistant to both atrazine and 2, 4-D amine were also found (Table 2.1).

Table 2.1 Frequency of resistance to chlorsulfuron, atrazine, and 2,4-D amine in wild radish populations randomly collected from across the Western Australian wheatbelt.

Herbicide	Herbicide Group	Resistant (%)	Developing Resistance (%)
Chlorsulfuron	B	35	25
Atrazine	C	6	68
2,4-D amine	I	5	62

(Walsh *et al.* 2005b)

In an another study, Owen *et al.* evaluated the frequency of herbicide resistance in *L. rigidum* across the WA wheatbelt. Very high frequencies of resistance to ALS (group B) and ACCASE (group A) inhibiting herbicides were observed in *L. rigidum* populations (Table 2.2). Almost 90% of *L. rigidum* populations contained individual plants with resistance to group B sulfonyl urea herbicides. Similarly, around 70% of *L. rigidum* populations contained plants that were resistant to the group A herbicide diclofop,

comprising 37% resistant and 30% developing resistance. One quarter of populations were developing resistance to trifluralin group D (24%). Only 6% of populations were susceptible to all of these herbicides. In contrast, 64% of the populations were resistant to both group A and group B herbicides.

Table 2.2 Frequency of resistance of randomly collected *L. rigidum* populations across the Western Australian wheatbelt.

Herbicide	Group	Resistant (%)	Developing (%)
Diclofop	A (fop)	37	30
Clethodim	A (dim)	0.5	7.5
Sulfonylureas	B	68	20
Trifluralin	D	0.25	24

(Owen *et al.* 2005)

Quinlan (2002) tested in field herbicide resistance in *L. rigidum* against certain herbicides. *Lolium rigidum* resistance to fluroxypyr-butyl at 64 g ha⁻¹ was extreme with only 4% of paddocks surveyed considered susceptible. Resistance to sethoxydim at 149 g ha⁻¹ was also extreme with only 11% of paddocks susceptible. Only 58 and 62% of paddocks were susceptible to clethodim at 66 g ha⁻¹ and fluroxypyr-butyl + fenoxaprop at 84 g ha⁻¹ respectively. Twenty seven percent of the paddocks tested were susceptible to sulfometuron at 150 g ha⁻¹.

Owen (2005) evaluated the level of herbicide resistance in *L. rigidum* in 503 randomly selected cropping practices, in 15 agronomic regions. Very high frequencies of resistance to the group B and group A herbicides were recorded. Eighty eight percent of *L. rigidum* populations were resistant or developing resistance to group B sulfonyl urea herbicides. Sixty seven percent of the populations were resistant or developing resistance to the group A herbicide diclofop and 24% were developing resistance to trifluralin (group D).

Llewellyn *et al.* reported that *L. rigidum* was found in 91% of the 523 wheat crop fields sampled. Chi square tests indicated sulfonylurea, clethodim and diclofop resistance status. Thirty eight percent of the 153 fop susceptible populations and 40% of the 149 fop resistant populations were present at < 1 plant m⁻². Regression analysis showed no significant association between resistance classification and density. Clethodim resistance currently remains relatively rare.

Roy and Jackson (1996) evaluated the clethodim (Group AII) option for use against a ‘fop’ (Group AI) resistant *L. rigidum* population and found that between 1993 and 1995 the population had moved from being partially resistant to haloxyfop to one exhibiting total resistance. At the same time the degree of resistance to sethoxydim had increased markedly to a level which would not allow its commercial use. The profile of clethodim performance had not changed with the top rate of 60 g ha⁻¹ maintaining a high degree of efficacy. The efficiency of clethodim was markedly reduced by cutting the rate to 42 and 30 g ha⁻¹.

The proportion of populations resistant to diclofop vary greatly between agronomic areas (Llewellyn and Powles 2000). In one area it was very high with 73% being resistant; in contrast no diclofop resistant populations were found in another area. Overall, of the 185 populations tested, 46% were classified as resistant or developing resistance to diclofop. The overall percentage of tested paddocks classified as resistant or developing resistance to chlorsulfuron was 64%. All populations classified as resistant to chlorsulfuron were resistant to sulfometuron.

Based on the above findings, herbicide resistance in *L. rigidum* populations is highly prevalent in Western Australia. The data indicate major resistance problems in *L. rigidum* against herbicides from group A, B, C, D and M plus the development of other significant resistance problems. The longer history of conservation tillage in WA has most likely contributed to these resistance levels.

Victoria

Henskens *et al.* (1996) performed the first major survey on the occurrence of herbicide resistant *L. rigidum* in Victoria and found that three of the four herbicide resistant *L. rigidum* populations were resistant to the group A herbicide diclofop methyl (Table 2.3). Full resistance was detected for only two herbicides, diclofop-methyl and the sulfonylurea (SU), chlorsulfuron. Herbicide resistance in *L. rigidum* was not restricted to group A and B herbicides and some degree of resistance appeared to be developing to all the four herbicides.

Table 2.3 Response of *L. rigidum* populations in Victoria to individual herbicides.

Herbicide	Metribuzin	Chlorsulfuron	Diclofop	Sethoxydim
Group	C	B	A	A
HR present	-	1	3	-
Developing HR	3 ^A	22	5	11
Cross-HR	3	4	1	5

HR = Herbicide resistance

(Henskens *et al.* 1996)

Cross-HR = developing cross/multiple-resistance

^A = All populations developing cross resistance.***South Australia***

Heap and Knight (1990) reported variation in herbicide cross resistance in *L. rigidum* resistant to diclofop-methyl in a study conducted in Adelaide. None of the populations were cross-resistant to glyphosate or propham. All the populations showed some level of cross-resistance to the other herbicides (fluzifop-butyl, haloxyfop-methyl, sethoxydim and chlorsulfuron), but there was considerable variation between populations in this resistance. The variation could not be related in any simple manner to the origin of the populations in Australia, nor to their past histories of herbicide application.

In another study, populations of *L. rigidum* in South Australia that have been found to be resistant to glyphosate had some resistance to the 'fop' herbicides (group A). More than 50% had high levels of resistance (greater than 30% survival of the fops) but only 10% had resistance to the 'dims' (group A). Two populations had resistance to the group B herbicides usually at low to moderate levels, (10-30% survival) (Matthews 2002).

New South Wales

A survey of commercially available *L. rigidum* seed in New South Wales showed that 58% of these samples were resistant to at least one herbicide. Seventy seven percent of samples tested were resistant to group AI, 40% to group B and 22% to group AII herbicides. Lower levels of resistance were found to group D (8%), group C (1%) and group M (0.4%) herbicides (Broster and Pratley 2006). Storrie and Cook (2002) conducted field trials on the Liverpool plains of northern NSW to compare a range of herbicide treatments for controlling glyphosate resistant *L. rigidum*. Glyphosate at 3240 g ha⁻¹ gave a 53% reduction in number of spikelets 90 days after treatment (DAT), while fluazip butyl (212

g/ha), clethodim (72 g ha⁻¹) and glyphosate trimesium (720 g ha⁻¹), gave 83, 96, and 8% reduction respectively. Results of field trials conducted the following year indicated that glyphosate (720 g ha⁻¹) and paraquat (450 g ha⁻¹) gave 71% and 95% control of *L. rigidum* at 30 DAT respectively.

New South Wales appears to be developing similar resistance levels to WA with high levels of resistance in *L. rigidum* against group A and B and lower resistance against group C, D and M herbicides.

In summary, the Australian continent is facing the worlds worst herbicide resistant populations. In all the states, *L. rigidum* is found to be either resistant to groups A, B, C, D and M or developing resistance to these groups.

2.3. Seedbank size and composition

The size and composition of the weed seedbank are considered good indicators of future weed infestations. Knowledge of the level of weed seedbanks in the soil provides an insight into the possible build up of some weeds and decrease of others over a specified time period.

Schweizer *et al.* (1998) analysed the seedbanks for Colorado cornfields and suggested that 14 annual broadleaf species and seven annual grass species were identified in the 50 seedbanks sampled after the fields were tilled. *Amaranthus retroflexus* and a mixture of *Setaria viridis* and *Setaria glauca* weed species were encountered the most, occurring in 90 and 54% of the fields, respectively.

For most species in a study in Canada, plant density was correlated with either the previous or current year's seedbank in a spring barley/red clover cropping system on clay soils. Correlations between midseason plant populations and subsequent seedbanks confirmed the role of residual populations in replenishing the seedbanks, including those of perennials like *Elytrigia repens* and *Taraxacum officinale* (Legere *et al.* 2005).

The Liverpool Plains region of northern New South Wales is considered to be part of the northern grain region of Australia and provides a wide range of grains, oilseeds and pulse crop to the nation. The sudden build up of glyphosate resistance in *L. rigidum* populations

in wheat cropping systems on the Liverpool Plains poses a serious threat to the grain industry (Storrie and Cook 2002). Characterisation and monitoring of *L. rigidum* seedbanks may provide better insight into its changes in this area and enable farmers and farm advisors to design management programmes to better reduce seedbank levels of *L. rigidum* and other weed species.

Data on seedbank composition in arable soils is limited in Australia; however studies conducted in other countries suggests variation in the weed seedbank due to factors such as geographical distribution of fields, the varying mortality and dormancy characteristics, climate (temperature and rainfall), weed management, cover crop canopy and biology of individual weeds.

Variations with tillage and crop rotation

Tillage and crop rotations can have a major effect on *L. rigidum* populations and seedbank over time. The impact of cereal crops on the seedbank level is very dependent upon how competitive the crops are with *L. rigidum*. Pulses can be a weak point in the cropping rotation for herbicide resistant *L. rigidum* management due to their non competitive growth habit. Windrowed canola was quite effective in reducing or at least maintaining *L. rigidum* seedbank levels, with mechanical topping having a similar effect to cutting hay in southern Australia (GRDC 2000).

Crop sequence and tillage system also influence the density and diversity of weed seedbanks of other weed species and germinable weed seed communities in no-tillage differed in composition from those under conventional and minimum tillage systems (Sosnoskie *et al.* 2006).

Distribution of weed seedbanks in the soil profile is highly dependent on crop rotations and are usually confined within the top 0-20 cm depth of soil (Buhler *et al.* 2001). Roberts and Chancellor (1986) studied seedbanks at Warwick, U.K. and found that the number of viable seeds in the 0-15 cm soil layer, sampled in 1972 or 1973 was in the range from 1500 to 67,000 seeds m⁻². The most pronounced fluctuation was involved in *Alopecurus myosuroides*, which tended to increase where winter cereals were grown and *Poa annua* which increased where grass leys were established.

Annual grass seedbanks preceding corn tended to be higher following the hay years of a 4 year rotation than following the wheat year of a 3 year rotation at Beltsville, USA

(Teasdale *et al.* 2004). According to Davis *et al.* (2005), the average decline of seedbanks in bare and vegetated treatments was 46.3 and 43.2% per annum, respectively in a corn/soybean/wheat sequence in Michigan, USA on a silt loam soil.

The tillage system and the cover crop type had a significant effect on the weed seedbank density after 7 years of different cover-crop-maize management systems in Pisa, Italy (Moonen and Barberi 2004).

In contrast to the above findings, tillage systems were found by Barberi *et al.* (1998) to have no significant effect on the weed seedbank composition. Rather, weed control efficacy was the factor responsible for changes in seedbank composition under four crop management systems *viz.* conventional (ploughing, pre-emergence herbicides), organic (ploughing, physical weed control), reduced input (rotary harrowing, post-emergence herbicide) and strip-cultivation (no-tillage, herbicides at sowing and post-emergence herbicide)

In comparison with the overseas data discussed above, seedbank studies in Australia are limited. The overseas data suggest major changes in level/species which are dependent on crop/pasture type and sequence, tillage type, weed management regimes. This is also likely to be similar for Australian conditions.

Variation with time

Tillage and crop rotations have significant influence on the composition of weed population and seedbank under different management systems. However, Felix and Owen (2004) found that tillage and crop rotations did not influence the weed seedbank. The weed seedbank densities varied with the years and time of soil sampling under a conservation reserve program (CRP) where sites had a uniform stand of CRP cover that prevented annual weed establishment. A competitive cover crop canopy in CRP probably reduced weed seedbanks by the suppression of weeds and seed production. Felix and Owen (2001) similarly reported that weed seed population densities tended to be greater in autumn under USA conditions but declined significantly by the time of the spring sampling.

Mickelson *et al.* (2004) quantified the cumulative and annual rates of *Eriochloa villosa* seed bank emergence patterns at Wisconsin, USA. Annual rates of mortality ranged from 50 to 92% and varied between seed banks established in different years when compared within the same year; older seed banks had higher rates of mortality than younger seedbanks.

Bekker *et al.* (2000) performed trials in the Netherlands and suggested that the number of seeds of many late successional species showed a significant increase during succession with only two characteristic late species present in the seedbank of the early stage of each series.

Variation between sites

Seedbank composition may vary between field sites with the same crop rotation. A range of results at three different fields for each autumn to spring sampling sequence in a no-tillage soybean/wheat/corn rotation (Webster *et al.* 2003). Similarly, seedbank levels and composition varied between locations in Prague (Kropac 1966).

Seedbank composition is greatly influenced by different climatic regions (Roberts 1981). Relatively, few species were prominent in seedbanks throughout temperate regions of the U.K. *Chenopodium album* and *Stellaria media* were major contributors to seed banks in cool temperate regions, while *Amaranthus* spp., *Echinochloa crus-galli*, and *Portulaca oleracea* were dominant in warm-summer temperate areas.

Similarly, weed composition is highly affected by varying ecological zones and soil properties. Chikoye and Ekeleme (2001) measured the weed flora and seedbanks in the savannah of West Africa and found a total of 88 weed species. Species richness in the seedbank, summarised by zone, followed a similar trend to that observed in the above ground weed flora: southern guinea savannah (SGS) > coastal derived savannah (CDS) > humid forest fringes (HFF). Overall, seed density and species diversity of the seed bank in the Netherlands was higher in a wet than a dry chronosequence.

At a more local level, seedbank composition did not solely depend on the abundance of species in the field but on the number of seeds shed per plant (Chauvel *et al.* 1989) and the seeds of most species in the soil seedbank had patchy distribution at Dijon, France,

indicating that the distribution of seeds is probably due to both biological and agricultural factors (Dessaint *et al.* 1991).

Variations with soil depth

Seedbank composition varies with soil depth. Seed bank populations of *Orobanche crenata* in *Vicia faba* were characterised by Granados and Torres (1993). The soil seed density increased from year to year and was higher in the surface layer (5-10 cm depth) than at greater depths (20-25 cm). The seed bank level was affected by the previous infestation severity and also by other environmental factors, such as rainfall, wind and tillage practices which led to the dispersion of seed.

Similarly, 85% of all the seed in the reduced tillage and 28% of those in the conventional tillage were in the 0-5 cm depth layer (Pareja *et al.* 1985). Also, Khedir and Roeth (1981) assessed the seed populations of *Abutilon theophrasti* in six continuous-corn fields at Nebraska, USA. The field population means ranged from 34 to 88 million viable seeds ha⁻¹, averaging 51 million in the top 20 cm of soil. Seventy percent of these seeds were found in the 0-10 cm depth, with a range from 61% to 75% for the six fields.

Tillage systems and soil types strongly affect the distribution of seedbanks at various depths. Ridge tillage (RT) had a larger soil seedbank (2,992 seeds m⁻²) than conventionally ploughed fields (CT) (1,481 seeds m⁻²) at Quebec, Canada. The top 5 cm of the 15-cm soil core contained 35 and 46% of all weed seed in CT and RT systems, respectively (Vanasse and Leroux 2000).

Generally, distribution of seeds with depth was highly dependent on crop management systems which in turn were greatly dependent on weed control strategies undertaken. Little work appears to have been published in Australia in this area.

2.4. Longevity and viability of seeds of *L. rigidum* and other weeds

Populations of annual weeds in cropping systems are determined largely by prior weed seed production and the storage of seeds in the soil as seed banks. One of the processes that determines emergence of *L. rigidum* from soil is seed dormancy. Like other grasses, *L. rigidum* seeds are dormant at the time of ripening, although this period of innate dormancy is fairly short (Peltzer and Matson 2006), though a proportion of the seedbank persisted for

several years in a tillage experiment conducted in Western Australia. Tillage increased the emergence of *L. rigidum* in the first year. The *L. rigidum* seedbank of viable seeds declined at a rate of 70 to 80% per annum while *Avena fatua* declined by 80% in the first year but only 50% in the second (Peltzer and Matson 2002a).

In the soil, a number of edaphic and environmental variables often simultaneously interact with varying effects on *L. rigidum* seeds. The major factors affecting dormancy change are exposure to light, rainfall, temperature, the gaseous environment, the depth of burial and soil type. Depending upon the location of the seeds in the soil profile and climate, *L. rigidum* seeds are thought to behave differently. Little has been known specifically about the effect of soil type and rainfall on the viability/longevity and emergence of *L. rigidum* in soil. This information could be used to develop and improve current control and management strategies.

Effect of depth of burial

Lolium rigidum

Cheam and Lee (2005) found that *L. rigidum* seeds have shorter life-span in the warmer northern wheatbelt than in the cooler southern wheatbelt of Western Australia. The life span does not extend beyond 4 years at a soil depth of 15 cm or more. The reduction in seed survival loss is depth dependent, being faster at greater depth mainly due to seed decay (Table 2.4).

Table 2.4 Seed survival of *L. rigidum* at various depths two years after burial at three different sites. Initial seeds buried = 100

Depth (cm)	Viable seed remaining (%)		
	Mt Barker	Northam	Chapman Valley
0	15.0	10.3	10.7
1	9.0	12.7	7.7
5	9.3	11.0	1.3
10	7.0	6.0	0
15	7.7	2.3	0

(Cheam and Lee 2005)

Burial of seed has variable effects on the germination and survival of seeds of certain weed species. Depth of burial has a pronounced effect on the survival of *L. rigidum* seeds. After 2 weeks of burial in Western Australia, only 10% of seeds survived at 2 cm compared with more than 75% at 5-14 cm. The percentage of seeds surviving for 8 weeks at depths of 8,

11 and 14 cm was 48, 68 and 70% respectively. Seed germination accounted for nearly all of the seed losses at 2 and 5 cm, but at 11 and 14 cm no seeds germinated and losses were due entirely to the death of seeds. At 8 cm both germination and death of seeds contributed to seed loss (Gramshaw and Stern 1977).

Phalaris spp.

Taylor *et al.* (2005) studied the emergence and persistence of *P. paradoxa* seeds in no-till and minimum-till situations and at different burial depths in a sub-tropical environment at Toowoomba, Australia. Burial depth and soil disturbance significantly influenced seedling emergence and persistence of seed. Emergence was least from seed on the soil surface, and from that buried at 10 and 15 cm depths in undisturbed soil.

Phalaris spp. behave similarly to *L. rigidum* in terms of biology and management and are a major grass weed in wheat cropping systems of southern Asia. Depth of burial had a strong influence on seed longevity by affecting the seed germination and decomposition at Karnal and Hisar in India (Franke *et al.* 2002). Om *et al.* (2003) conducted trials at Kaul, India and found that the dormancy of *P. minor* seed was less than 60 days and viability less than 10 months under field conditions.

Other weed species

Like *L. rigidum*, *Avena fatua* and *Echinochloa crus-galli* either have acquired resistance to certain herbicides or are a potential threat to acquire it in Australia. In these two grasses viability tended to decrease with increase in depth of burial (Miller and Nalewaja 1990). Buried populations of dormant and non-dormant *Avena fatua* seeds persisted less than 2 years, with depth of burial having very little influence on their survival in the USA (Zorner *et al.* 1984b).

Omami *et al.* (1999) examined the changes in germinability, dormancy and viability of *Amaranthus retroflexus* in Sydney, NSW, Australia and found that irrespective of placement, all seeds lost viability at an exponential rate over time. However, the decline was most rapid for those on the surface, whereas the loss in viability became less with increased depth of burial.

Roberts and Feast (1972) determined the fate of seeds of some annual weeds at different depths at Warwick, England and found that for many weed species, burial of seeds even at very shallow depths is sufficient to depress germination and to favour survival of viable seeds which could then germinate following cultivation. In contrast, Benvenuti *et al.* (2001) reported that seed burial of *Rumex obtusifolius* inhibited germination in proportion to depth in field experimental work in Pisa, Italy. Recovery of ungerminated seeds shows that excessive burial did not impede seedling emergence but rather prevents seed germination. Burial of small seeded species both delayed and reduced seedling emergence as compared to surface sown seed. In contrast, germination and emergence of the larger-seeded species was increased with burial at Reading, UK (Froud-Williams *et al.* 1984).

Seeds may undergo periods of dormancy. Mennan and Zandstra (2006) at Samsun, Turkey reported that *Veronica hederifolia* seeds exhumed from the soil were dormant at the beginning of an experiment and exhibited dormancy/nondormancy/conditional dormancy cycling throughout the experiment. Seeds retrieved from the soil surface germinated well initially, but germination decreased as depth of burial increased.

Deeply buried seeds of *Carthamus lanatus* lost at a slower rate than seeds closer to surface. The most rapid decrease in seedbanks of *C. lanatus* was in the first 6-month period, and clearly more seeds were lost (dead) in the first year than in the second. Seed numbers remaining in bags varied with depth and significant time x depth interactions occurred (Grace *et al.* 2002).

Campbell and Nicol (2002) reported that increased depth of sowing at Bigga and Boorowa NSW, Australia led to reduced emergence of *Carex appressa* and almost all the decline in germination occurred in the first 6 months after burial. Likewise, emergence decreased exponentially at greater depths for *Chenopodium album* and *A. retroflexus* (Mohler and Galford 1997). Highest emergence of *Urochloa subquadriflora* occurred from the seeds placed on the soil surface in Florida, USA. Emergence declined sharply as seed depth increased, with no emergence from seed placed below 7 cm (Teuton *et al.* 2004).

Burial of seeds induced dormancy in certain weed species in Western Australia (Dunbabin and Cocks 1999). Burial inhibited germination of non-dormant seeds of *Arctotheca calendula*. Buried seed lost the ability to germinate under test conditions, indicating that

burial induced secondary dormancy. In contrast buried seeds of *Bromus diandrus* lost their dormancy much faster than surface seeds in both the Chapman and Mt Barker accessions in Australia (Cheam 1986).

Studies conducted both overseas and in Australia indicate that seeds of various weed species respond differently when placed at varying depths. For most of the weed species, emergence decreased with increase in depth and seed survival was greater in undisturbed soil. Seeds placed on the surface of the soil lost dormancy more quickly. Emergence was found to be more weather specific and seeds lost more viability in the first year under ideal conditions. Burial of small seeded species both delayed and reduced seedling emergence as compared with surface sown seed while the opposite trend was observed for large-seeded species.

Effect of rainfall

Dormancy of *L. rigidum* seed varies with the rainfall pattern (Ellery and Chapman 2001) and seed dormancy biology can vary substantially between sites and between years. This variation is likely to interact with rainfall patterns to affect weed emergence and seedbank longevity of *L. rigidum* in the northern wheat belt of Australia.

Boyd and Acker (2003) at Manitoba, Canada found that all the perennials tested had the greatest percent emergence when seeds were placed on the soil surface at constant field capacity while emergence was reduced when seeds were placed on the surface and soil moisture fluctuated. There were no significant differences in germination percentage of *Striga hermonthica* under various water regimes (Gbehounou *et al.* 2003).

Adequate rainfall received at the start of the growing season would prompt seeds of *Bromus diandrus* to germinate completely if the seed was slightly covered with soil to exclude light (Cheam 1986). Spears *et al.* (1980) reported that *Centaurea maculosa* and *C. diffusa* require more than 55% initial soil moisture to initiate emergence, with 65- 70% being optimum. Emergence rate decreased with soil moisture above 70%. Similarly, an increase in soil moisture content beyond field capacity had a drastic effect in decreasing germination (less than 12%) of *Phalaris minor* seed irrespective of temperature (Om *et al.* 2005).

These studies suggest that although maximum emergence in most of the weed species occurred at field capacity it was affected by fluctuations in soil moisture. For some species, emergence increased with an increase in soil moisture and it decreased for other species where soil moisture was above 70%. Seeds of certain weeds had high levels of dormancy and decreased viability over time under dry conditions. Loss of dormancy depended on rainfall.

Effect of soil type

Soil types play an important role in affecting the dormancy and emergence of seeds. Soil type, temperature and moisture affected the survival and seasonal germination of seeds of *Avena fatua* and *A. sterilis* ssp. *ludoviciana* at Narrabri and Coolah NSW, Australia (Table 2.5) (Quail and Carter 1968).

All seeds on the surface of the soil had decomposed after 18 months and there were no significant differences in the viability of seeds at 25, 150, and 225 mm depths (Table 2.5). The percentage of seeds that decomposed without producing seedlings increased sharply with the depth of seeding. This suggested that germination had occurred but that the seedlings had failed to emerge from the soil. Other seeds had decomposed without germinating. There was no significant difference in the survival of seeds placed under the high and low moisture regimes. Significantly more seeds survived in the Narrabri (grey soil of heavy texture) than in the Coolah soils (red loam) probably because the Narrabri soil was more prone to cracking.

Table 2.5 Effect of soil type and moisture regime on the viability of seeds of wild oats buried for 18 months.

Depth of seeding (mm)	Seeds viable after 18 months (%)*			
	Narrabri soil		Coolah soil	
	High #	Low	High	Low
0	0.00	0.00	0.00	0.00
25	2.25	3.25	1.00	0.00
75	8.75	2.00	1.75	6.25
150	1.25	3.25	0.00	0.00
225	1.50	1.75	0.50	0.25
Mean	2.75	2.05	0.65	1.30

watering frequency

(Quail and Carter 1968)

* L.S.D. = 0.83 ($P = 0.05$)

Viable seeds recovered after a 2 year burial experiment showed that lowest number of seeds were found in Chapman valley soil (brown sand) compared with Northam (sandy loam) and Mt. Barker (brown loamy sand) (Cheam and Lee 2005).

Soils with a pronounced clay matrix impeded germination of buried seeds and induced seed dormancy at Pisa, Italy. Clay soils can present the ideal pedologic conditions for the accumulation of an elevated persistent seedbank (Benvenuti 2003).

2.5. Predicting weed emergence

WEEDDEM is an interactive software package designed to predict the timing of emergence for the two most troublesome weeds of southern Australian dryland cropping regions - *L. rigidum* and *R. raphanistrum*. WEEDDEM uses emergence models based on Australian laboratory and field data. The software model predicts weed emergence based on microclimatic conditions near the soil surface and relates these conditions to seed dormancy status and extent and timing of seedling emergence. The software is targeted for use by farmers, farm advisers, and extension personnel so that they can better anticipate weed control needs (Walsh *et al.* 2002). The literature discussed below briefly describes similar types of models used by various researchers for different weeds and cropping situations.

Ekeleme *et al.* (2005) predicted the seedling emergence of *Ageratum conyzoides* using a model based on hydrothermal time. Hydrothermal time at 2 cm soil depth was calculated from soil moisture and soil temperature simulated from several micrometeorological and soil physical variables. The model was developed using 5 years of field emergence data from a continuous corn-casava production system in southwestern Nigeria. The percentage of cumulative seedling emergence from the 5 year data set was fitted to cumulative soil hydrothermal time using a Weibull function. The model was evaluated by comparing percentage of cumulative emergence values from Mudlike (south eastern Nigeria) and Los Banos (Philippines) with the predicted values. At Mudlike, the model usually predicted the emergence of *A. conyzoides* in all the treatments adequately. At Los Banos, predicted seedling emergence closely matched observed field emergence. Small discrepancies between predicted and observed emergence occurred, especially during early and late phases of emergence, but otherwise, the model predictions matched observations remarkably well.

Mohler (1993) modelled the effects of tillage on emergence of weed seedlings at New York, USA. The model explores the relationship between three processes: 1) the vertical distribution of seeds in the soil column, 2) the rate of emergence of seedlings from the soil as a function of depth of seed burial, and 3) the survival of seeds, also as a function of their depth of burial. Tillage operations are assumed to change the vertical distribution of seeds in the soil but not to affect the relation between seed depth and emergence or survival. The model further assumes that emergence occurs shortly after tillage, and that all seed mortality occurs after emergence but before the next tillage event.

Studies were conducted in Quebec, Canada to calibrate and validate a mathematical model previously developed to predict *Chenopodium album* seedling emergence at different corn seedbed preparation times (Leblanc *et al.* 2004). The model was calibrated for different types of soils by adjusting the base temperature of *C. album* seedling emergence to the soil texture. The calibrated model provided a good fit of the field data and was accurate in predicting cumulative weed emergence in different soil types. There were no differences between observed and predicted values. This model could be adapted to model other weed species whose emergence is limited by low spring temperatures.

Grundy *et al.* (1999) extended a vertical movement model at Warwick, UK, to include the effects of four cultivation implements on the horizontal displacement of weed seeds. These implements were a rotovator, a spring tine cultivator, a spader and a power harrow. This investigation combined the depth of burial and vertical movement models to simulate the likely outcome of different sequences of spring tine, spader, rotavator and power harrow on subsequent weed seedling emergence. The findings of a series of simulations were viewed in the light of existing methods of weed control based on soil cultivation, for example, the 'stale seed bed' technique. The model provides the basis for a decision support system to aid with the control of weeds. Additionally, it provides a research tool to improve our understanding of the dynamics of the weed seed bank and the implications of seed bed preparations for future populations. The combined model has helped to identify areas of weed seed ecology requiring further study, essential for the development of true dynamic models.

2.6. Management of *Lolium rigidum* and other weed populations and seedbanks

Zero tillage farming is often considered as the most profitable, consistent and environmentally friendly farming practice in relation to other tillage options. Long term zero tillage systems have compelled farmers to use herbicides with a similar mode of

action year after year with little choice of alternatives. This has resulted in selection of individuals in certain *L. rigidum* populations in cropping regions of Australia resistant to glyphosate and many group A and B herbicides. As a result, *L. rigidum* has become an increasingly important weed in Australian agriculture as a whole and more recently in northern NSW and southern Queensland. Besides *L. rigidum*, several other weeds flourishing in cereal cropping areas are already showing resistance to several herbicides and many more are on the verge of acquiring resistance. This has resulted in researchers looking for alternatives to herbicides which can be incorporated into current farming systems. As seed banks are the main source of future weed infestations, seed bank depletion is important in reducing weed levels. Depletion of seed banks through the use of modified tillage practices may help to reduce reliance on herbicides and associated problems of resistant weeds. Management practices which can be altered include modifications to the tillage system used, crop rotations, herbicide use, burning as well as other cultural weed control techniques.

Tillage

Tillage had long been used as the main means for controlling weeds in Australian agriculture, but the introduction and successful use of no tillage farming systems for years have caused farmers to rely more heavily on herbicides for controlling emerging weed infestations. Tillage is again being looked at as one of the alternative measures to control herbicide resistant weeds. Tillage may be used to reduce weed density, biomass and the seed bank of the persisting weeds apart from any positive effects on yield and yield attributing characters.

Effect on Lolium rigidum

Mouldboard ploughing can often bury seed deep in the soil, resulting in effective weed control. Mouldboard ploughing (MBP) was successful in burying the majority of *L. rigidum* seed (Douglas and Peltzer 2004, Douglas *et al.* 2004, Peltzer *et al.* 2003) thereby

preventing the emergence of a large numbers of seedlings in the absence of post-emergent selective herbicide use at Katanning and Beverley, Western Australia.

Peltzer and Matson (2006) similarly reported that windrow burial by a MBP (after burning) was the most successful control strategy reducing *L. rigidum* densities by over 99%. This resulted in a two fold increase in cereal yields probably because MBP buried the seed at a depth greater than 15 cm, from where seedlings were unable to germinate.

The size and composition of the seedbank is highly influenced by tillage compared with crop rotations. In a post-emergence herbicide based application system in central Italy, total weed density ranged from highest to lowest in no tillage (NT), minimum tillage (MT) and chisel ploughing (CP) plots (Barberi and Cascio 2001). Similarly, perennial and overwintering weed species increased with reduced tillage compared with ploughing in autumn and spring in Norway (Torresen *et al.* 2003).

Whilst overseas data is limited on the effects of tillage on *L. rigidum* populations, Australian data suggest a major reduction in *L. rigidum* populations due to use of MBP. No tillage generally increased weed infestations.

Effect on Alopecurus myosuroides

Alopecurus myosuroides is the major grass weed in Europe and has acquired resistance against certain herbicides. It behaves similarly to *L. rigidum* in terms of biology and management. *Alopecurus myosuroides* infestation was greater on direct drilled and tine cultivated plots rather than on ploughed plots (Moss 1979, Pollard *et al.* 1982) in the UK.

Moss (1980b), also reported that for a crop established after ploughing (20 cm deep) the *A. myosuroides* infestation was unaffected by seed production in the previous crop. In contrast, tine cultivations (15 cm deep) gave results similar to those found with direct drilling. It is suggested that these differences between cultivations were due to presence of old seeds in the soil which were brought up to the soil surface by ploughing, but not by cultivations which did not invert the soil.

In winter wheat under Mediterranean dryland conditions in Turkey, the total weed density for 2 years was significantly higher for disc tillage followed by rototiller (non inversion

implements) and MBP. The lower density in MBP may have occurred because MBP stimulated the germination of weed seeds buried by autumn ploughing, and thus emerging seedlings got damaged by sensitivity to early autumn freezing and this reduced the seedbank. There was no significant influence on grain yield as a result of tillage in the first year, however, in the second year, the significant higher grain yield was observed with the rototiller (Ozpinar 2006).

Tillage types affect the distribution of weed species. The annual grass weeds *A. myosuroides* and *Poa* spp. were more numerous on uncultivated and on shallowly-cultivated plots at Berkshire and Oxfordshire in the UK. Perennial and wind borne species were also more frequent on uncultivated plots (Froud-Williams 1983b).

Results obtained on *A. myosuroides* suggest that the infestations are lowest in MBP plots; however, with other cultivation types they are largely dependent on the previous year's seed shed. Populations are higher in uncultivated and shallow cultivated plots.

Effect on other weeds

Weeds react differently to varying tillage operations and this in turn affects the occurrence of weeds. *Chenopodium album* and *A. retroflexus* were associated with MBP and *Digitaria sanguinalis* with NT plots in Canada (Swanton *et al.* 1999). Clements *et al.* (1996) reported similar trends with corn-soybean rotations in Canada. They found that seedbank populations of *C. album* with MBP were greater than those with ridge-till (RT) and NT. Chisel ploughing (CP) seed bank populations were greater than those in RT. Chisel ploughing and MBP systems generally had higher aboveground plant populations than the other two systems.

Buhler and Oplinger (1990) on the other hand found that *Chenopodium album* densities were not greatly influenced by tillage treatments, but *A. retroflexus* densities were generally highest in the CP system. MBP always had greater *Abutilon theophrasti* densities than NT and NT always had greater *Setaria faberi* densities than MBP. *Setaria faberi* and *A. retroflexus* were difficult to control when tillage was reduced, while *A. theophrasti* became less of a problem. The changing pattern of weed establishment with different tillage practices might be due to the differences in germination characteristics of weed species. Further work by Buhler (1992), on other weeds, showed a variable effect of

tillage. Average *A. retroflexus* densities in NT and CP systems were high compared with very low densities in MBP and RT. This was probably due to tillage systems having a greater influence on weed densities than on emergence patterns.

Tine and MBP cultivation influenced the decline of *A. fatua* seed production associated with spring barley cropping in the UK (Wilson 1978). In contrast, Martin and Felton (1993) conducted experimental work at Tamworth, Australia, and showed that, in the third and fourth years of a continuous wheat rotation, cultivated fallow using CP increased *A. fatua* density and reduced grain yield compared with a NT fallow. The seed reservoir at the end of the experiment was smaller under a NT fallow regime. The rotation of wheat with sorghum was the most effective means of reducing the *A. fatua* seed reservoir.

Tillage alone (compared with no till) resulted in 88%, 78%, 64% and 31% control of *Elytrigia repens* in Canada (Chandler *et al.* 1994) with autumn MBP, spring MBP, autumn soil-saver (modified chisel plough with twisted shovels) and spring soil-saver tillage, respectively. Wilson *et al.* (1986) conducted similar experiments in the USA to find that control of *P. annua*, *Bromus* spp. and *Anthemis arvensis* was nearly complete with MBP. Likewise, Blackshaw *et al.* (1994) carried out trials in Alberta, Canada, with continuous wheat and wheat-canola rotations. They found that NT plots often had more weeds than MBP plots and there were only limited tillage effects on weed populations within the wheat/fallow rotation. Cardina *et al.* (1991) reported that highest seed density of mixed weed species in USA was found in no tillage plots (77,800 m⁻²) and the lowest in mouldboard ploughed plots (400 m⁻²) due to better weed control in tillage treatments and to the stimulatory effects of tillage in inducing weed seed germination. With an increase in soil disturbance, the species numbers decreased. In contrast, Ghosheh and Hajaj (2005) showed that tillage in the form of MBP increased the seedbanks for most of the species present at Irbid, Jordan.

Seed size may influence the distribution of seeds under different tillage systems. Deep burial of seed of small seeded species by MBP reduces germination and emergence. Conversely, seeds of large seeded species remain near the soil surface in conservation tillage systems, inhibiting establishment and reducing seed burial that contribute to reinfestation following subsequent tillage operations (Warnes and Andersen 1984).

Certain weeds increase with one tillage type and decrease with another. *Anacyclus clavatus*, *Portulaca oleracea*, *Papaver rhoeas*, *Torilis nodosa*, *Arabidopsis thaliana*, *Draba verna*, *Amaranthus albus*, *Scandix pecten-veneris* and *Veronica triphyllos* increased

under NT in central Spain. Conversely, the presence of *Polygonum aviculare* and *Raphanus raphanistrum* was highest in plots under MBP (Dorado *et al.* 1999). No tillage, CP, and MBP favoured different weeds in studies in the USA (Cardina and Herms 2002, Spandl *et al.* 1999), whereas *Epilobium* spp., *Sonchus arvensis* and *Myosotis arvensis* were more abundant in NT than in CP and MBP in an experiment initiated at Zurich, Switzerland (Streit *et al.* 2003).

Similarly, in other studies tillage had a large effect on weed diversity and density. No-tillage promoted the highest weed species diversity, CP was intermediate, and MBP resulted in the lowest species diversity (Murphy *et al.* 2006). Whereas, *P. annua*, *Matricaria* spp., *Aphanes arvensis*, *Cerastium holosteoides* and *Sambucus nigra* were favoured by reduced cultivation and by direct drilling at Oxford, U.K. *Polygonum aviculare* and *Fumaria officianalis* were discouraged by shallow soil disturbance and *A. fatua* was favoured by CP (Pollard and Cussans 1981).

In Argentina, the MBP crop had the lowest seedbank density and there was no treatment difference in density or composition at 0-5 cm and 5-10 cm depths whereas NT had a denser seedbank, especially in the upper part of the soil profile. Thus the data strongly support the hypothesis that the systems causing less disturbance allow the build up of a larger and more diverse soil seed bank.

The review suggests that lower weed density is associated with MBP. Seedbanks of weeds generally increase with reduction in tillage. No tillage was associated with an increase in the number of seeds of different weed species and density and composition of the seedbank varied accordingly to tillage system and depth used. Different species were favoured by each tillage type.

Straw burning

The burning of wheat straw was practised by grain growers for many years as a tool to manage weed infestations, but due to changing environmental priorities, it is not practised widely now in many developed countries including Australia. However, in some developed and most of the third world countries, straw burning is still used and considered a useful alternative weed management strategy. Researchers have proven the benefits of residue

burning in the past and this concept is again being explored by researchers as a simple alternative to managing both herbicide resistant and susceptible weeds.

Straw burning helps in reducing the number of weed seeds being shed on the soil surface by killing the seeds being shed due to high temperatures associated with burning. Straw burning destroyed many *Alopecurus myosuroides* seeds lying on the soil surface and, compared with straw removal, resulted in a smaller weed infestation in a subsequent direct-drilled winter wheat crop at Oxford, U.K (Moss 1980a).

Burning of wheat straw followed by light CP can destroy a large number of weed seeds on the surface by both the action of burning and by disrupting newly germinated seeds by soil disturbance. Moss (1979) reported that for each straw treatment there was considerably more *A. myosuroides* under direct drilled and tine treatments than under ploughed plots. Straw burning reduced the amount of this weed appearing in the winter wheat crop with all three cultivation treatments. Thus the best control of *A. myosuroides* was achieved by straw burning followed by ploughing whilst, the highest infestation occurred when straw was baled followed by direct drilling of the crop.

In another study, Moss (1980b) suggested that fresh seed of *A. myosuroides* were also reduced by straw burning. Cultivation tended to mask the beneficial effect of straw burning probably because old viable seeds were brought up to the soil surface while burnt seeds were buried.

Any unburnt seeds remaining after straw burning treatment followed by ploughing were returned to the soil surface and germinated vigorously compared with seeds on the surface which were not burnt. Seeds that survived burning, germinated more rapidly (Moss 1987) probably due to breaking of dormancy or by provision of a better environment for germination. Similar results were reported by Froud-Williams (1983a) in a straw disposal trial in UK. Straw-burning substantially reduced the numbers of seedlings and seeds present at the soil surface. With cultivation there appeared to be some stimulation of germination. Although straw burning reduced the population density, the reproductive capacity of surviving plants was improved.

Similar effects of burning on the germination and viability of seeds has been demonstrated by Wilson and Cussans (1975) working at the same location as Froud-Williams. Total viable seeds of *A. fatua* from the burnt stubble of a barley crop were reduced by 50% or more at each of four recovery dates. The stubble between the straw swathes did not burn, so that the large number of seeds between the burnt straw swathes reduced the overall effect of burning. Loss of dormancy of *A. fatua* seeds following burning resulted in more seedlings appearing in autumn. Where the stubble was cultivated, burning increased the number of seedlings by 250% and where it was not cultivated, by 330%. Cultivation encouraged seedling emergence and the interaction of cultivation and burning produced the highest number of seedlings. The two effects of burning, killing seeds and reducing dormancy of the survivors were additive and increased the total drain on viable seed reserves. Burning also reduced the numbers of viable seeds recovered from the soil the next year.

In contrast, Om *et al.* (2003) working at Kaul, India found that the emergence of *Phalaris minor* in farmers' wheat fields was 42-80% lower in the fields where wheat straw was burnt than where it was removed. Seed numbers collected from farmers' fields clearly showed that there was 60% less germination where wheat straw was burnt after combine harvesting compared with straw removal.

Burning of straw is helpful in destroying the seeds on the soil surface. Furthermore, there are techniques that might help to have a greater burn of the straw and the weed seed on the soil surface. A windrow treatment at Geraldton, Western Australia produced a burn that was much hotter and longer lasting than the standing stubble treatment, which destroyed *L. rigidum* and *Raphanus raphanistrum* seeds and reducing the subsequent emergence of *L. rigidum* seedlings at the start of the following growing season (Walsh *et al.* 2005a, Walsh *et al.* 2006).

Results from Australia and abroad suggest that straw burning destroys a large proportion of seeds lying on the soil surface and stimulates other unburnt seeds to germinate rapidly. A combination of straw burning followed by ploughing considerably reduced weeds appearing in winter wheat but improved reproductive capacity (greater flowering and tillering) of surviving seeds.

Herbicides

Many novel herbicides are currently being used for *L. rigidum* control in wheat (as well as other crops) due to the *L. rigidum* developing resistance to many commonly used herbicides (Newman and Adam 2004b). Due to changes in the weed flora, new herbicides are continuously being introduced to gain a substantial control of different weed species in the wheat crop. *Lolium rigidum* is a problem weed which is difficult to control under Australian conditions due to the inheritance of resistance against certain herbicides. Farmers have been using herbicides with different modes of action to control this weed but many of them are no longer effective. The literature cited below is an attempt to collate information concerning the use of different types of herbicides by farmers to control *Lolium* spp. and other weeds. All the herbicide rates mentioned are of active ingredients unless otherwise specified.

Lolium rigidum

There has been a high level of adoption of herbicides for *L. rigidum* control since their introduction in the early 1970s. Farming systems have continually changed with the availability of new herbicide products, such that pre-planting tillage has been replaced by non-selective herbicide use and crop selection products on many farms. *Lolium rigidum* has been a particular target of selective herbicides due to its widespread distribution (Matthews 1996).

Spraying of herbicide susceptible *L. rigidum* at Geraldton, Western Australia, when the grass was at the 1-3 leaf stage (Newman and Adam 2003b, Newman and Nicholson 2001) resulted in a complete kill for both Spray.Seed (135 g/L paraquat and 115 g/L diquat) and glyphosate. At full label rates, several mixtures provided good control (>95%) of both *L. rigidum* and *Raphanus raphanistrum* at Merridin and Northam in Western Australia, (Borger *et al.* 2004b) these being diuron + glyphosate, carfentrazone-ethyl + glyphosate, diuron + metribuzin + glyphosate, metribuzin + carfentrazone-ethyl + glyphosate, and diuron + metribuzin + carfentrazone-ethyl + paraquat + diquat. None of the individual chemicals and none of the mixtures applied at partial rates achieved this level of control. Double knock of a full rate of glyphosate followed by a full rate of Spray.Seed five days later is the best practice to control *L. rigidum* at the 3 to 4 leaf stage (Borger *et al.* 2004a, Newman and Adam 2003a, 2004a).

Mixing one or more herbicides may provide some synergistic effects in effectively controlling herbicide susceptible and resistant *L. rigidum* plants and thereby help in prevention of herbicide resistance. Application of glyphosate followed by Spray.Seed was generally more effective than the reverse sequence or a single herbicide application (Borger *et al.* 2003) at Merridin and Northam in Western Australia. The herbicides should be applied at the 3 to 6 leaf stage of herbicide susceptible *L. rigidum* and there should be a 2 day interval between the first and the second herbicide application. Newman and Adam (2002) from Geraldton, Western Australia, however reported that glyphosate and Spray.Seed alone gave 79% and 71% control respectively. Trifluralin and its mixes were the best of all the treatments to control *L. rigidum*.

Addition of 250 mL ha⁻¹ of metolachlor to the trifluralin + triallate mixture appeared to reduce crop yield without improving the control of the weed (Newman and Adam 2004b). Yield 250 EC (oryzalin + trifluralin) gave good control with excellent crop safety. Minkey *et al.* (2000), working at Merredin and Northam, found a strong interaction between seeding rate, row spacing and herbicide use. *Lolium rigidum* numbers and hence seed head production can be reduced to very low levels when trifluralin is used in conjunction with high seeding rates and/or narrow row spacing. Hashem *et al.* (2000), working at a similar location, evaluated a number of herbicides and found that trifluralin and triasulfuron reduced *L. rigidum* head numbers by 92-99%.

Crabtree (2000) reported that trifluralin activity can be greatly improved for effective control of *L. rigidum* with no till wheat seeding into thick standing wheat stubble by applying it immediately before seeding with a solid carrier such as granules and limesand. However, Crabtree (1999), suggested that a combination of trifluralin with triasulfuron and diuron provided better control of *L. rigidum*. Similarly, Cheam *et al.* (1998) in Western Australia, reported that despite resistance to aryloxyphenoxy propionate herbicides (fops), *L. rigidum* could still be controlled to some extent by alternative herbicides such as triasulfuron, trifluralin and diuron in combination with various non chemical practices.

The most effective autumn combination in one study in the UK was pre triallate followed by chorotoluron plus graduate (diflufenican + flurtamone) applied at the 2-3 leaf stage of the weed. This gave an average 97.9% control of herbicide susceptible *L. rigidum*. In

contrast, control dropped to 87.8% with the triallate followed by isoproturon + pendamethalin (Monsanto 2002). King *et al.* (2003) working at Virginia, USA, indicated that levels of *L. rigidum* control similar to standard treatments containing cynazine can be realized through the use of gramoxone plus atrazine or glyphosate applied alone or in combination with either atrazine or rimsulfuron + thifensulfuron. Reeves and Lumb (1974) evaluated herbicides for effective control of *L. rigidum* in oilseed rape, field peas and lupins and found that diallate, trifluralin and simazine reduced the populations in all the experiments. Pre-planting incorporated treatments were generally more effective than post sowing or post emergence treatments in oilseed rape and field peas.

Application of herbicides later in the growth cycle but before the weeds flower has found an important place in controlling herbicide resistant *L. rigidum*. Glyphosate (450 g L⁻¹) was most effective when applied at the rate of 225-450 g ha⁻¹ during the heading and anthesis stage of *L. rigidum*, reducing the number of filled seeds produced compared with unsprayed plants. Spray.Seed (paraquat 135 g L⁻¹ + diquat 115 g L⁻¹) was most effective when applied post-anthesis, during the milk and early dough stages of seed development at a rate of 125-250 g ha⁻¹, resulting in the production of few viable seeds. Glyphosate application also reduced the proportion of seeds exhibiting dormancy (Steadman *et al.* 2006).

The foregoing discussion indicates that, greater control of *L. rigidum* can be achieved when application of chlorsulfuron is altered to pre-emergence rather than early post-emergence. Maximum control of *L. rigidum* can be achieved for most of the herbicides sprayed at the 1-3 leaf stage. Tank mixtures were found effective in providing better control rather than herbicides applied alone, specifically trifluralin. Pre-plant application of herbicides are generally more effective than post sowing or post-emergence treatment in reducing the populations of *L. rigidum* seedlings in fields of oilseed rape, field pea and lupins.

Lolium multiflorum

Lolium multiflorum (Italian ryegrass) is another species from the Poaceae which has an economic impact in European and American agriculture. Control of *L. multiflorum* by mesosulfuron-methyl + iodosulfuron-methyl sodium (AE F130060 03) was similar to

diclofop-methyl and was greater than that by chlorsulfuron + metsulfuron, chlorsulfuron + metribuzin, sulfosulfuron, tralkoxydim, and clodinafop propargyl in Virginia, USA (Bailey and Wilson 2003). High rates of diclofop + metribuzin and s- metolachlor provided equally effective *L. multiflorum* control in 1999 at Maryland, USA, averaging 85% or greater, whereas s-metolachlor at 0.43 kg ha⁻¹ or greater provided 85% control (Ritter and Menbere 2002).

Similar studies were conducted by Jordan *et al.* (2001) in Louisiana, USA and their results indicate that glyphosate controlled *L. multiflorum* more effectively than paraquat when applied at growth stages ranging from two leaves to heading. Oxyfluorfen, thifensulfuron plus tribenuron, and 2,4-D did not change the level of control by glyphosate or paraquat. Clethodim controlled *L. multiflorum* more effectively than glyphosate or paraquat in one of two experiments.

Griffin (1985) evaluated certain herbicides to control herbicide susceptible *L. multiflorum* in a wheat crop at Louisiana, USA, and found that *L. multiflorum* control using chlorsulfuron at 35 g ha⁻¹ was significantly higher when applied pre-emergence (pre) than early post emergence with two to four leaves. Metribuzin applied at 420 g ha⁻¹ early post emergence controlled more than 95% of the *L. multiflorum*, but control was unacceptable when applied late post emergence when *L. multiflorum* was at the mid tillering stage. Diclofop-methyl provided excellent control when applied early post emergence at 560 g ha⁻¹. Wheat yields averaged over years, for early post applications of chlorsulfuron at 35 g ha⁻¹, metribuzin at 280 and 420 g ha⁻¹ and diclofop at 560 g ha⁻¹ were 22, 22, 24 and 20% higher respectively than the untreated stands.

Phalaris minor

Phalaris minor behaves similarly to *L. rigidum* in terms of biology and management and is the major grass weed in wheat cropping systems in southern Asia. The tank mixture of chlorsulfuron either with pendimethalin or trifluralin at 1430 + 70 g ha⁻¹ provided effective control of both *P. minor* and broadleaf weeds at Karnal, India. The number of spikes and wheat yield increased with the increase in the rate of chlorsulfuron from 20 to 40 g ha⁻¹. The tank mixture of pendimethalin or trifluralin with chlorsulfuron was as effective in increasing the grain yield of wheat as the application of each of these herbicides alone

(Singh *et al.* 2005). At a similar location, Singh *et al.* (2004) found that oryzalin at 1500 g ha⁻¹ reduced the dry weight of *P. minor* by 91% compared with the weedy control and was on a par with isoproturon, sulfosulfuron and pendimethalin. Grain yield with the oryzalin treatments was similar to the weed-free treatment. The highest grain yield of wheat was recorded with isoproturon followed by sulfosulfuron and oryzalin at 1500 g ha⁻¹.

2.7. Conclusions

The review of literature has been helpful in identifying gaps in knowledge and has provided useful background information necessary to understand the research questions posed in this thesis. The following points are relevant to the present context.

- Published seedbank studies in Australia are relatively limited; overseas data suggest that tillage, crop rotations and herbicides strongly influence the level of seedbanks and seedling emergence of weeds.
- Variation in seedbank levels of different weed species is largely due to factors such as geographical distribution of fields with varying mortality, dormancy characteristics, climate (temperature and rainfall), management issues, cover crop canopy and weed biology of individual weeds.
- Weed emergence and the persistence of seedbanks in soil varies markedly with different weed species.
- There is little information on the changing patterns of *L. rigidum* seedbanks in the northern grain region of NSW.
- Different weed species vary in their dormancy/viability and seedling emergence in soil depending on several factors with greater influence from depth of burial and moisture levels over a period of time.
- Seeds of *L. rigidum* buried deep die mainly due to seed decay rather than failed germination or emergence.

- Depth of burial has a pronounced effect on the survival of *L. rigidum* seeds. Seed germination accounts for nearly all of the seed losses at 2 and 5 cm depth.
- Emergence is weather specific and seeds of many species lose their viability in the first year of burial under ideal conditions.
- Cracking soils exhibit more seedling emergence and soil with a pronounced clay matrix can impede germination of buried seeds and induce secondary seed dormancy more than other soils.
- There is little information available about the impact of different factors such as depth, rainfall and soil types on the dormancy/viability of *L. rigidum* over time.
- Some populations of *Lolium rigidum* are already resistant to glyphosate and there are cases of multiple and cross resistance in populations spread over various locations in Australia.
- Due to continuous use of herbicides for many years, *L. rigidum* populations have been seen to be increasing under the no-till systems as it is acquiring resistance to one or more herbicides.
- There is little information on the effects of tillage systems and straw burning on *L. rigidum* and other weed species densities and seedbanks in Australia.
- Mouldboard ploughing increases the emergence of certain weeds whilst also decreasing that of others. In particular it decreases the emergence of *L. rigidum* plants.
- Tillage is an important mechanism influencing composition of weed flora. Secondary soil disturbance affects the emergence of weeds but these effects are highly dependent on seasonal variations in rainfall.
- Straw burning destroys a large proportion of seeds lying on the soil surface and prompts other unburnt seeds to germinate rapidly. A combination of straw burning

followed by ploughing can considerably reduce weeds appearing in winter wheat but can improve the reproductive capacity of surviving seeds.

- Maximum control of *L. rigidum* can be achieved for most of the herbicides sprayed at the 1-3 leaf stage. Tank mixtures have been found to be effective in providing better control rather than the application of individual herbicides, particularly trifluralin.
- The WEEDDEM model has been used in South Australia and Western Australia to predict *L. rigidum* seedling emergence but there are no data on its performance in the northern region of NSW.
- Tillage and burning may be better options for control of herbicide resistant weeds. In order to have effective management, seedbank studies along with these alternate management practices may be helpful in combatin herbicide resistance.

Chapter 3. Evaluation of herbicides

3.1. Introduction

Annual ryegrass (*Lolium rigidum*) is one of the most important weeds of the grain cropping regions of southern Australia (Western Australia, South Australia, Victoria, and New South Wales)(Pannell *et al.* 2004). Since the 1970s, herbicides have been used extensively to control *L. rigidum* and other weeds in crops. The over reliance on herbicides has resulted in the evolution of herbicide resistance in many *L. rigidum* populations (Gill 1995, Llewellyn and Powles 2001, Preston *et al.* 1999). *Lolium rigidum* resistance is considered to be among the most important examples of economic disruption due to herbicide resistance in world agriculture (Powles *et al.* 1997).

Lolium rigidum has been controlled by a range of non-selective herbicides applied prior to sowing of the crop, by selective herbicides in conjunction with the sowing operation and by post-emergent herbicides (Broster and Pratley 2006). The resistance of *L. rigidum* to diclofop-methyl, a group AI herbicide, was the first confirmed case of herbicide resistance in Australia (Heap and Knight 1982). It was shown subsequently that this population was cross-resistant to other herbicides to which the population had never been exposed (Heap and Knight 1986). Since that time, resistant *L. rigidum* biotypes have been frequently reported for a range of selective herbicides used in Australia (Powles and Matthews 1992).

Glyphosate is the world's most widely used broad-spectrum herbicide. It is used in a variety of situations, including broad-acre cropping, horticulture, viticulture, in fallows and along fence lines and drainage ditches (Dyer 1994). In Australia, resistance to glyphosate in *L. rigidum* was first reported in 1996 (Pratley *et al.* 1996). The increased reliance on non-selective herbicides is now causing some concerns particularly for glyphosate and cases of resistance to this herbicide are now being widely documented (Powles *et al.* 1998, Pratley *et al.* 1999). According to the Australian Glyphosate Sustainability Working Group (GSWG), 10 new populations of glyphosate resistant *L. rigidum* were identified in 2006. This is more than twice the number reported in 2005. To date, 54 confirmed glyphosate resistance populations have been reported from Western Australia, South Australia, Victoria and New South Wales (Preston 2006).

The incidence of glyphosate resistance is still relatively low but such jumps in the number of resistant populations should serve as a cue for growers to adopt practices that minimise

the risk of developing glyphosate resistance (E-lert 2006). Multiple resistance to several herbicide groups occurs in *L. rigidum* (Thill and Lemerle 2001). In a random survey in Western Australia, 46% and 64% of *L. rigidum* populations were resistant to diclofop-methyl and chlorsulfuron, respectively, and 37% were resistant to both herbicides. A large proportion exhibit multiple resistance to ACCase- and ALS- inhibiting herbicides (Llewellyn and Powles 2001). Surveys in Victoria in 1992 indicated that 35% of fields sampled had *L. rigidum* resistance to one or more selective herbicides (Henskens *et al.* 1996) whereas a 1993 survey of the mid-north region of South Australia showed the incidence to be 40% (Nietschke *et al.* 1996).

Seedbanks are the major source of future weed infestations for many species (Marks and Mohler 1985b). For effective management of *L. rigidum* (herbicide resistant and susceptible) populations weed seedbank depletion is required. A farm survey in the lower Liverpool Plains in northern NSW in 2001 showed that glyphosate resistant *L. rigidum* was present on at least 10 properties, with infestations varying from small patches of plants to being wide spread across the whole property (Storrie and Cook 2002). Improved understanding of the extent of herbicide resistance should aid the targeting of herbicide resistance-related research and extension to specific cropping areas (Orson 1999). For management of *L. rigidum* seed banks, it is important to know how the populations respond to different herbicides with the same or different modes of action. It is important to quantify the extent and severity of herbicide resistance (if any) in both resistant and susceptible populations of *L. rigidum*.

A measure of the extent of resistance also provides a useful benchmark for future monitoring of herbicide resistance development. Seeds of *L. rigidum* were collected from Tamarang, The Point property on the Liverpool Plains of northern NSW with confirmed glyphosate resistance but otherwise unknown herbicide susceptibility. Another sample of commercially available *L. rigidum* seed originating from Victoria and for sale as pasture seed for the Northern Tablelands and presumed susceptible to a range of herbicides was purchased locally for comparison purposes. A glasshouse trial was initiated during December 2005 to evaluate the two seed lots of *L. rigidum*. The 'resistant and the 'susceptible' seed samples were germinated and sprayed with five herbicides with a range of modes of action and the experiment was repeated in 2006. The aim of the trial was to assess the effectiveness of a range of commonly used herbicides and to determine levels of

cross/multiple resistance and susceptibility which could affect glyphosate resistant and susceptible *L. rigidum* control.

3.2. Methods

Site

A trial was initiated in a glasshouse at the University of New England Armidale, NSW (30°30'S, 151°40'E) under controlled conditions. Black plastic pots (15 cm diameter) were filled with medium heavy clay chocolate basalt soil (0-10 cm depth, pH 6.4, and 2.8% organic matter) collected from Laureldale Research Station, University of New England, Armidale.

Design

Each herbicide treatment (see below) was replicated three times in a factorial (chemical x seed sample x year x herbicide dose) randomised complete block design experiment.

Treatments

The treatments were as follows:

- two seed samples: one was considered as resistant to glyphosate with an unknown response to other herbicides whilst the other was for sale locally with an unknown history, but presumed to be susceptible to all the herbicides;
- five herbicides: these were glyphosate, diclofop-methyl, chlorsulfuron, sulfometuron-methyl and tralkoxydim (Table 3.1);
- six herbicide rates: 0.25x, 0.5x, 1x, 2x, 4x and 8x (x is the recommended rate);
- two years: first in 2005 and then repeated in 2006.

Table 3.1 Recommended rates of herbicides applied post emergence at the 2-3 leaf stage of *L. rigidum*.

Herbicide	Trade Name	Group	Active ingredient (g kg ⁻¹)	a.i rate (g ha ⁻¹)	Wetter	Rate of Wetter
Glyphosate	Roundup Max	M	576	650	-	
Diclofop- methyl	Hoegrass	A	375	375	BS 100	100ml 100L ⁻¹
Tralkoxydim	Achieve	A	400	200	Supercharge	750 ml L ⁻¹
Sulfometuron- methyl	Oust	B	750	300	BS 100	100ml 100L ⁻¹
Chlorsulfuron	Glean	B	750	15	BS 100	100ml 100L ⁻¹
Control	Water					

Sowing of L. rigidum seeds and spraying of herbicides

The pots were placed in the glasshouse after being filled with the soil. The soil in the pots were irrigated up to field capacity to settle the soil in the pots before sowing of seeds. Sowing of *L. rigidum* seeds was performed on 22 November, 2005 and 16 August, 2006. Twenty five *L. rigidum* seeds were sown per pot approximately 1-2 cm deep. The soil in the pots was watered immediately after sowing of the seeds. The temperature in the glasshouse ranged from 20°C at night to 30°C during the day with natural day length in 2005 and 15°C to 25°C in 2006.

A gas operated boom sprayer with 3 Teejet TT 11003 flat fan nozzles delivering 85 L water ha⁻¹, separated 50 cm apart, was used to spray each of the herbicides at the 2-3 leaf stage of *L. rigidum* seedlings. The sprayer was calibrated by adjusting the spraying speed on the unsown pots before the start of the trial. Accurate spraying speed was measured and used to calculate the exact chemical mixture requirement to be sprayed for each individual chemical. After spraying each herbicide, the boom spray was flushed with water to remove any of the previous residual herbicide content. The formula used was:

total water delivered = 600 x nozzle output / nozzle space (0.3 m) x speed;

where nozzle output = litres / minute water delivered from the nozzle;

nozzle distance = distance between the nozzles used (metres); and

speed = walking speed with sprayer in km hr⁻¹.

The herbicides were sprayed outside the glasshouse with sufficient care to avoid spray drift by the action of wind.

Data collection

One day prior to seedling spraying, *L. rigidum* seedlings in each pot were counted. The data on efficacy of herbicides (% control) were collected at 7, 14 and 21 days after spraying (DAS) of the herbicides. Plants were scored on a 0 to 10 scale where, 0 = all live plants and 10 = all dead plants per pot. The score was thereafter converted to percent (%) control for analysis of results. After conversion, the 0 represented 0% control, 1 and 10 represented 10 and 100% control respectively. The day after taking the final recording 21 DAS, all the live green *L. rigidum* plants were counted as a percentage of the original numbers emerged. The % live plants counted were categorised into regrown and survived plants here in this experiment. The regrown *L. rigidum* seedlings were the ones with abnormal stout bushy growth unlike the live normal plants. The survived plants were the ones which showed no or very little injury as a result of the herbicide application at increasing doses.

The populations of *L. rigidum* were classified on the criteria defined by Llewellyn and Powles (2001). According to these criteria the population was resistant if more than 20% of the plants survived the herbicide treatment. Populations in which 1 to 20% of plants survived were classified as developing resistance and those classified as susceptible were where all the plants were killed. After final counting, the *L. rigidum* live above-ground plants were harvested from each pot separately and stored in paper bags for drying in a hot air oven for 3 days maintained at 60° C. After drying, the samples were weighed and divided by number of live plants in each pot representing the average *L. rigidum* dry weight per plant for each pot.

Data analysis

The non-linear least squares regression function in S-Plus 2000[®] was used to fit data to several response variables (MathSoft. 1999). The data for percent control (except sulfometuron) were fitted with the Michaelis-Menten function:

$$Y = a * x / (b + x) \quad \text{(Equation 3.1)}$$

where a = upper asymptote, b = level of curvature (rate of increase of the parameter)
 x = dose of herbicide.

The data for % control (scoring) of *Lolium rigidum* plants for sulfometuron were fitted with a linear model in R 2.3.0 (R Development Core Team). Data were modelled using linear regression:

$$Y = a + b \cdot x \quad (\text{Equation 3.2})$$

where $a = Y$ intercept, $b =$ slope and $x =$ dose of herbicide

The linear and non-linear regressions are presented with 95% confidence limits.

Diagnostic plots were used to check the homogeneity of variance and normality of the data for each response variable and no transformations were necessary. Generalised linear models (GLM) with a Poisson distribution were used to determine the effects of the treatments at individual points for percent control. The GLM output contained an Analysis of Deviance table with a Chi-square test for significance of the explanatory variables. Goodness of fit was confirmed by comparing the residual deviance with the underlying Chi-square distribution. The P values for GLM are presented in the results section to indicate the level of significance. Data for the *L. rigidum* dry weight, % plants survived and regrown, and % resistance levels were compared using means and standard errors represented as standard error bar plots as they could not be fitted well enough for any linear or non linear model.

3.3. Results

Percent control

The results for the individual herbicides evaluated in the trial are presented separately. The five way analysis of deviance table for percent control indicated that the four way interaction of dose x days after sowing (DAS) x seed x chemical, three way interactions of dose x DAS x chemical, dose x seed x year and dose x seed x chemical were significant in affecting the % control. Of the two way interactions and the main terms all were highly significant except the two way interactions of dose x DAS and DAS x year. The data were then fitted to a logistic regression model (Equation 3.1 and 3.2) and the a and b parameters used to interpret the change of percent control at increasing dosage rates from each treatment combination.

Chlorsulfuron

Percent control data for chlorsulfuron for year 2005 and 2006 are presented in Figure 3.1. Generally, with the increase in dose from 0.25x to 8x at 7, 14 and 21 DAS, the % control

increased for both the resistant and the susceptible *L. rigidum* plants in both years. None of the higher doses applied to either seed sample in either year were able to kill all *L. rigidum* plants (% control < 83%). The glyphosate resistant seed sample appeared to be controlled more than the susceptible counterpart at 7, 14 and 21 DAS at all the dose rates in both years. The rate of increase of the % control followed the similar trend at 7, 14 and 21 DAS during both the years. Greatest % control for the resistant (83%) and the susceptible (53%) seed samples during 2005 was experienced at the 8x dose and 21 DAS (based on the mean values). A similar pattern of results was obtained for both seed samples during 2006.

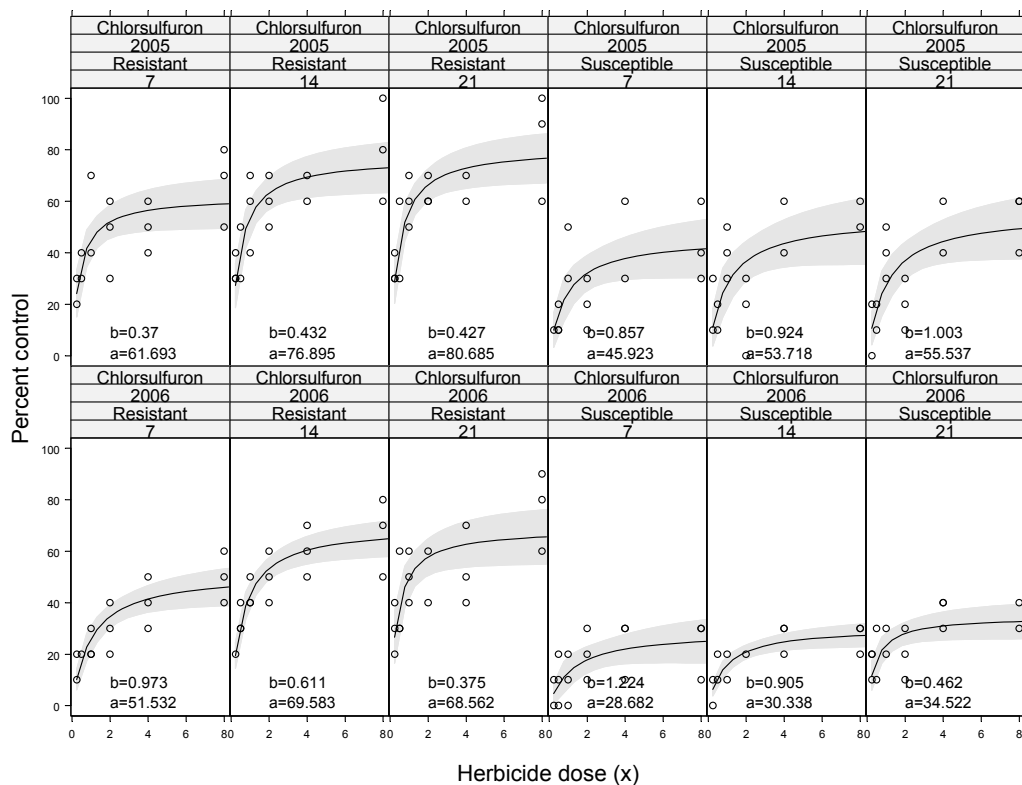


Figure 3.1. Effect of increasing doses of chlorsulfuron on the % control of glyphosate resistant and susceptible seed sample at 7, 14 and 21 DAS in 2005 and 2006. On the Y-axis, 0 = all live plants and 100 = all dead plants. Data were fitted with a non-linear regression (Equation 3.1) and 95% confidence limits. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. a = upper asymptote, b = rate of increase.

Within years, the plants receiving chlorsulfuron treatments during 2006 generally had lower % control for all the treatment combinations than 2005, but the trend during both the years was similar. The % control did not change significantly between 7 and 21 DAS for both seed samples during the first year. However, during 2006 it appeared to increase significantly for the resistant seed sample from 7 to 21 DAS. At the recommended dose

(1x), chlorsulfuron provided only 60% and 40% control at 21 DAS for the resistant and the susceptible seed samples respectively during 2005 (based on the mean values). The following year, the % control at 1x was 50% and 23% for resistant and susceptible seed samples respectively.

Diclofop-methyl

Generally, with the increase in dose of diclofop-methyl from 0.25x to 8x at 7, 14 and 21 DAS, the % control increased for both resistant and susceptible *L. rigidum* plants in both years. Overall, the % control achieved for different treatment combinations was greater during 2005 as compared to 2006 (Figure 3.2).

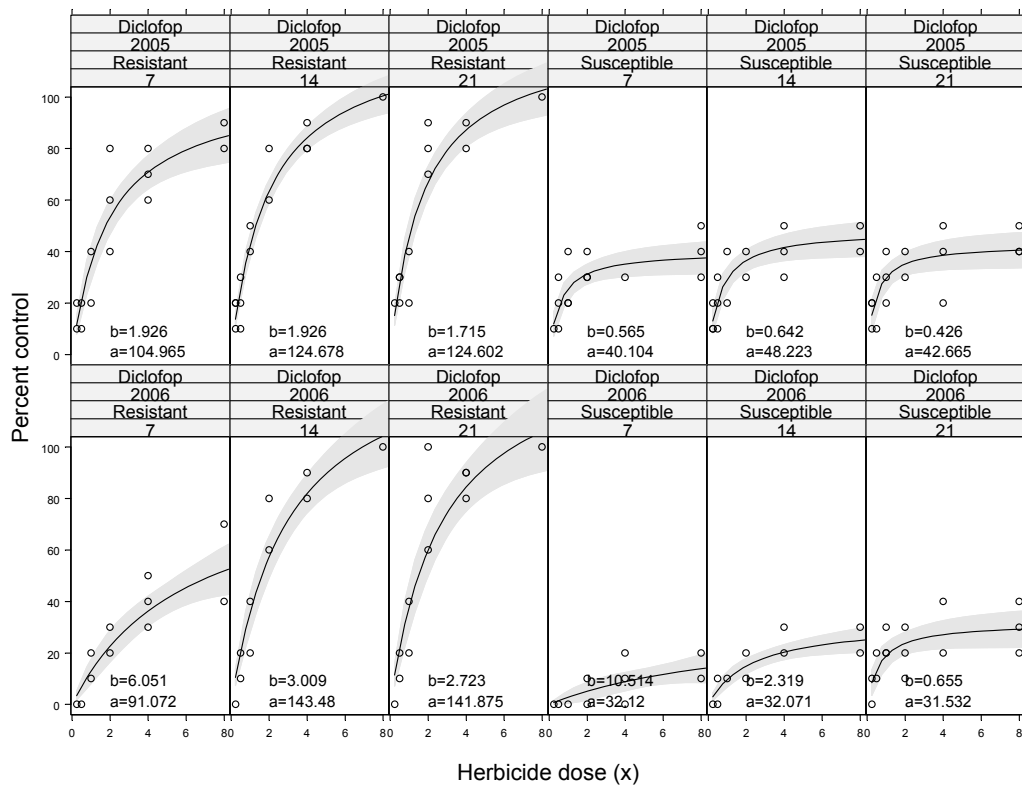


Figure 3.2 Effect of increasing doses of diclofop-methyl on the % control of glyphosate resistant and susceptible seed sample at 7, 14 and 21 DAS in 2005 and 2006. On the Y-axis, 0 = all live plants and 100 = all dead plants. Data were fitted with a non-linear regression (Equation 3.1) and 95% confidence limits. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. a = upper asymptote, b = rate of increase.

There appeared to be large % control variations between the resistant and the susceptible seed samples. In 2005, the % control for the resistant seed sample was significantly greater than the susceptible ones at the higher doses of diclofop-methyl and at all DAS. The

following year, the difference in % control was relatively greater than the previous year. The susceptible seed samples had the greatest rate of % control increase during 2005 ($b=0.56$) and 2006 ($b=0.65$).

During 2005, diclofop-methyl provided only 43% and 33% greatest control at 14 DAS and 1x dose for the resistant and the susceptible seed sample respectively (based on the mean values). However, in 2006 the % control was only 26% and 23% at 1x for resistant and susceptible seed samples respectively at 21 DAS. Diclofop-methyl attained 100% *L. rigidum* control for the glyphosate resistant seed samples at 14 and 21 DAS during both years. The susceptible seed samples during 2005 and 2006 provided a greatest of only 46% and 30% control even at the higher dose rate.

Glyphosate

There was a strong dose response on the % control of *L. rigidum* plants by glyphosate (Figure 3.3). The results for % control in both years were similar. At higher doses, 100 % control was achieved for both seed types and at each date.

The seed sample which was considered resistant to glyphosate experienced 100% control at 8x the herbicide dose whereas the susceptible seed sample attained this target at 4x dose at all the three DAS in both years. The rate of % control increase appeared to be greater for susceptible seed samples compared with the resistant counterpart during both the years and at all the three DAS.

On an average, at the recommended dose, glyphosate achieved 27% control of the resistant seed sample and 60% of the susceptible seed sample during 2005 (based on the mean values). Whereas, in the following year, the average % control at the recommended rate was only 28 and 42% for both the seed samples respectively. There appeared to be no significant difference for the % control obtained at different DAS during 2005 and 2006. Greatest rate of increase in % control during 2005 ($b=0.88$) and 2006 ($b=1.54$) was achieved from pots containing susceptible seed sample 14 DAS.

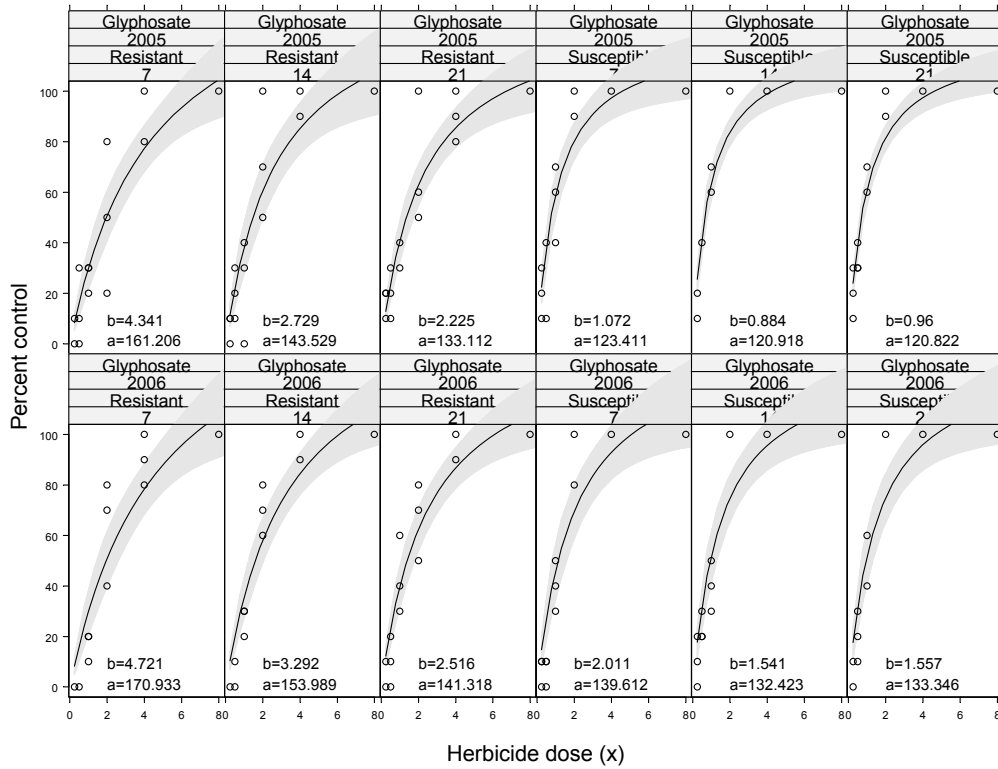


Figure 3.3 Effect of increasing doses of glyphosate on the % control of glyphosate resistant and susceptible seed sample at 7, 14 and 21 DAS in 2005 and 2006. On the Y-axis, 0 = all live plants and 100 = all dead plants. Data were fitted with a non-linear regression (Equation 3.1) and 95% confidence limits. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. a = upper asymptote, b = rate of increase.

Tralkoxydim

As with other herbicides, the dose rate of tralkoxydim had a significant effect on the % control of *L. rigidum* seedlings (Figure 3.4). Absolute *L. rigidum* control was achieved at 8x the recommended rate with the resistant seed samples at 14 and 21 DAS in both years. However, even at highest rate, susceptible seed samples were not controlled beyond 86% in both the years (based on the mean values). The rate of % control increase was greater for the susceptible samples ($b= 1.33$) compared with the resistant counterpart ($b= 2.14$) at 21 DAS during 2005. However, in 2006 the greater rate of increase was achieved by the resistant seed samples ($b= 4.02$) compared with the susceptible one ($b= 7.23$).

The average % control for resistant and susceptible seed samples at all the three DAS at 8x dose was 97% and 81% respectively during 2005 and it was 86% and 51% respectively during 2006 (based on the mean values). At the recommended dose, tralkoxydim was able to achieve an average (DAS) % control of only 44% and 34% for the resistant and the

susceptible seed sample during 2005 and 33% and 15% during 2006. The % control of the susceptible seed samples varied considerably between 2005 and 2006.

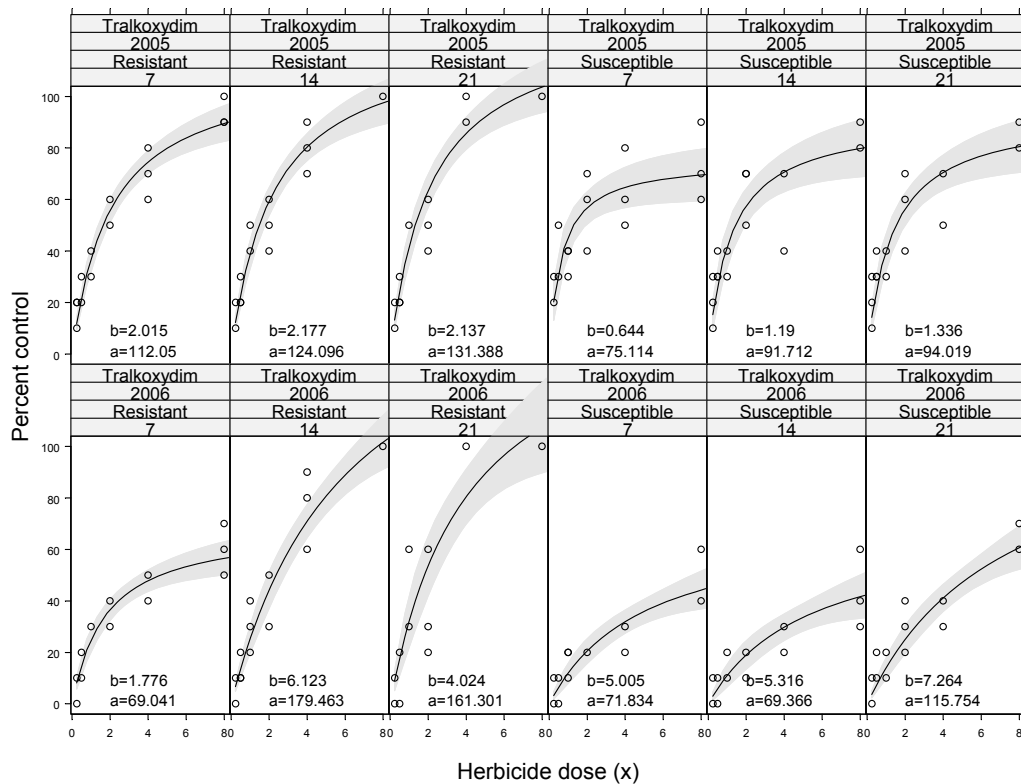


Figure 3.4 Effect of increasing doses of tralkoxydim on the % control of glyphosate resistant and susceptible seed sample at 7, 14 and 21 DAS in 2005 and 2006. On the Y-axis, 0 = all live plants and 100 = all dead plants. Data were fitted with a non-linear regression (Equation 3.1) and 95% confidence limits. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. a = upper asymptote, b = rate of increase.

Sulfometuron

There was a strong linear dose response to sulfometuron seed of *L. rigidum* over the three scoring dates during both years. However, in 2005 the dose response for the resistant seed sample at 14 ($P= 0.129$) and 21 DAS ($P= 0.396$) was not significant (Figure 3.5). Similarly, during 2006, the resistant seed sample at 21 DAS had a non significant dose response ($P= 0.396$).

Overall, the % control of the resistant seed sample was greater than the susceptible counterpart for all the dates during both years. At the recommended dose, the average % control of the resistant and the susceptible samples during 2005 was 77% and 54% whereas, in the following year % control was 82% and 35%. All the resistant seed samples

of *L. rigidum* were controlled at 21 DAS even at the lower dose rate of 0.25x in both years. The susceptible seed sample however, was not fully controlled at 8x the recommended dose rate. The trend for the rate of increase of *L. rigidum* control with increasing herbicide dose was virtually the same in each year.

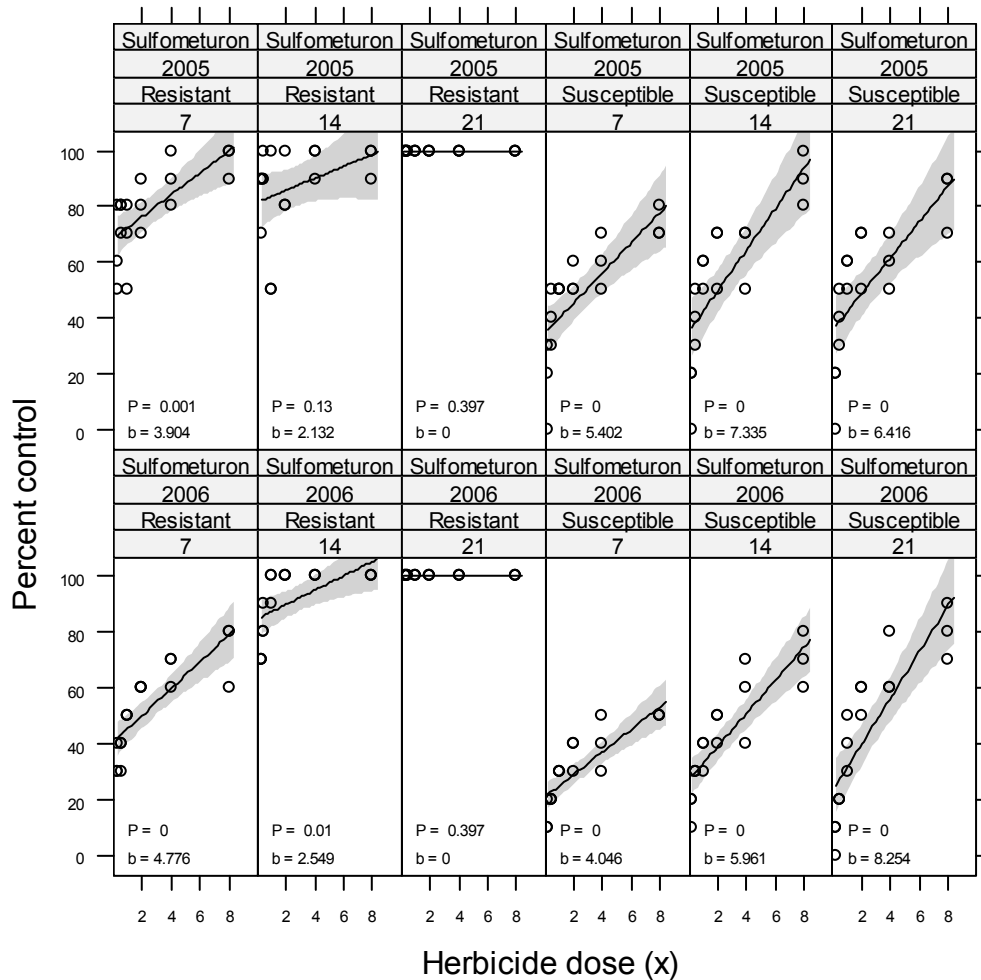


Figure 3.5 Effect of increasing doses of sulfometuron on the % control of glyphosate resistant and susceptible seed sample at 7, 14 and 21 DAS in 2005 and 2006. On the Y-axis, 0 = all live plants and 100 = all dead plants. Data were fitted with a linear regression (Equation 3.2) and 95% confidence limits. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

Lolium rigidum dry weight

The dry weight of survived and regrown *L. rigidum* plants was recorded at 21 DAS. The results for the individual herbicides are presented in separate graphs. The four way analysis of deviance for dry weight of *L. rigidum* showed that all the 4 way, three way and two way interactions and the main terms were significant except the three way interaction of dose x seed x year ($P= 0.20$).

Chlorsulfuron

Dry weights of *L. rigidum* plants sprayed with chlorsulfuron are presented in Figure 3.6. Generally, with the increase in dose rate there appeared to be a variable response in the dry weight for both the resistant and the susceptible seed samples in both years. During 2005, the overall dry weights of the susceptible and the resistant seed samples were not significantly different at any of the doses whereas in 2006, dry weight of the susceptible seed samples was significantly higher than the resistant counterpart at all the doses (Figure 3.6).

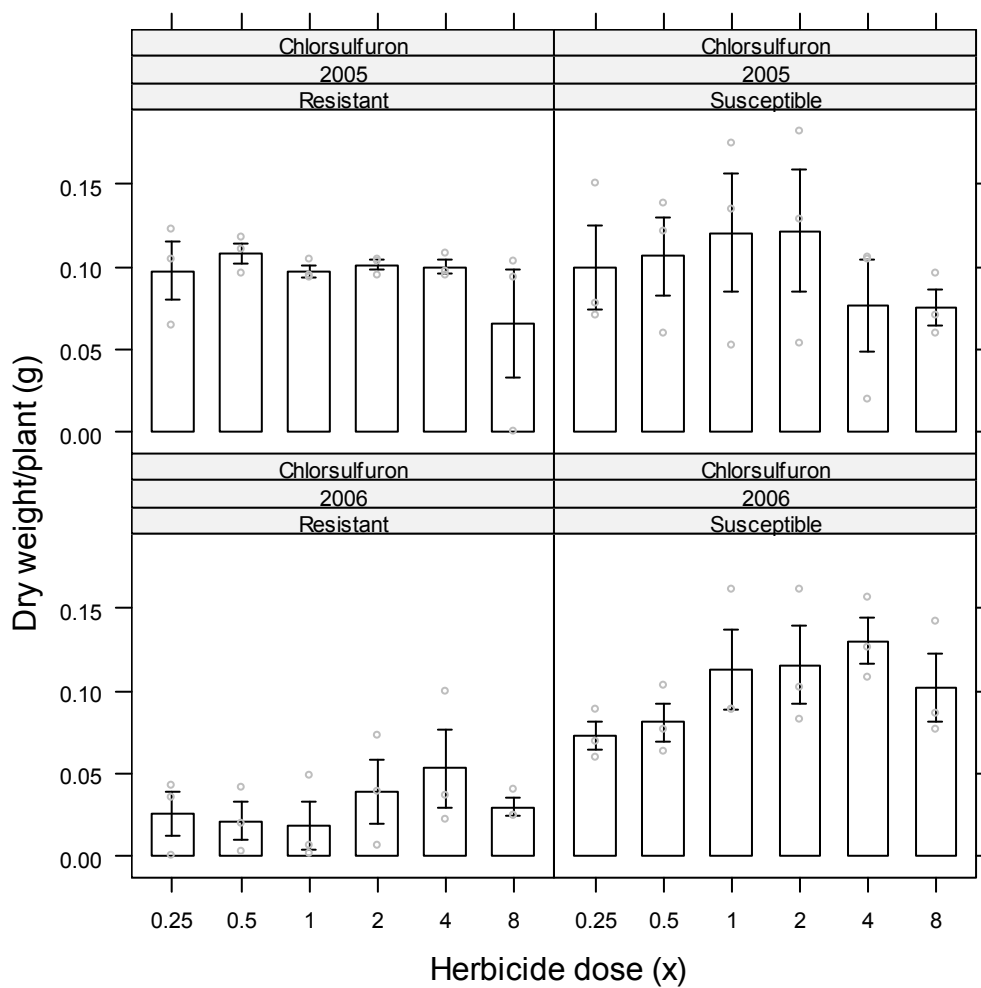


Figure 3.6 Effect of increasing doses of chlorsulfuron on the average dry weight of glyphosate resistant and susceptible surviving *L. rigidum* seedlings. Vertical bars represent the mean dry weight at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

There were no significant dry weight reductions with increasing dose rate for the resistance sample in 2005. For the susceptible seed sample, only the dry weight recorded at 8x was significantly lower than some of the other lower dose levels. Major dry weight reductions

occurred at all the dose levels for the resistant seed sample in 2006 with no significant differences between dose levels compared with the susceptible counterpart. For the susceptible seed sample, the dry weight of plants sprayed with the 0.25x dose were significantly lower than the 1, 2 and 4x dose levels.

Diclofop-methyl

In 2006, the dry weight of the susceptible *L. rigidum* plants was greater than the resistant sample (Figure 3.7). Highly variable dose responses were observed in both the years for all the treatment combinations.

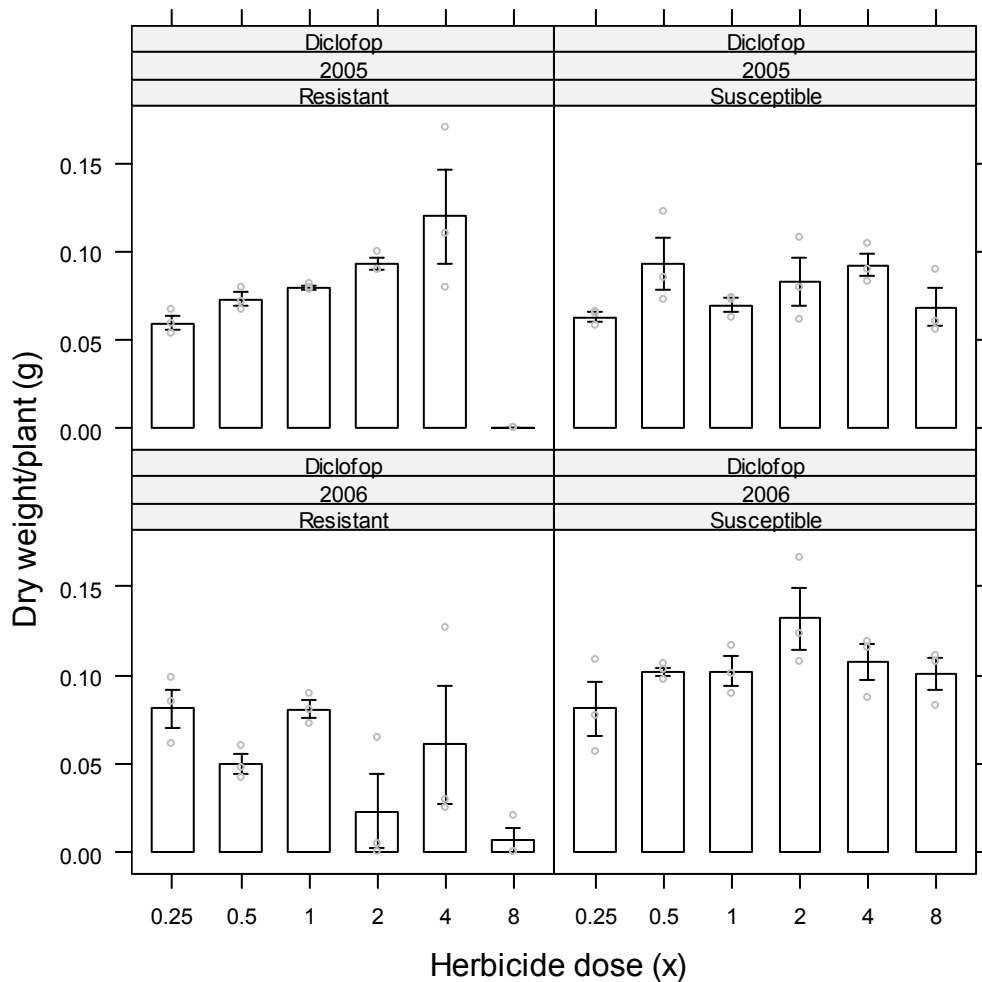


Figure 3.7 Effect of increasing doses of diclofop-methyl on the average dry weight of glyphosate resistant and susceptible surviving *L. rigidum* seedlings. Vertical bars represent the mean dry weight at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

At higher dose levels of diclofop-methyl, the dry weight of the susceptible seed sample was significantly higher in 2006 than in 2005. No *L. rigidum* plants survived in the pots sprayed with the 8x the recommended dose for the resistant sample in 2005.

Glyphosate

Increasing the dose rate of glyphosate generally reduced the dry weight of surviving seedlings except for the recommended rate (1x) treatment. No significant dry weight differences appeared to occur between the resistant and the susceptible seed samples within the year and between the years (Figure 3.8). Dry weight decreased strongly when the dose was increased above 1x for all the treatment combinations due to the lower number of live plants remaining per pot with increasing doses. For the resistant seed sample during 2005, *L. rigidum* dry weight was greatest and similar for first three doses and similar and lower at the other three doses. For the susceptible seed sample, minimum seedling dry weight was

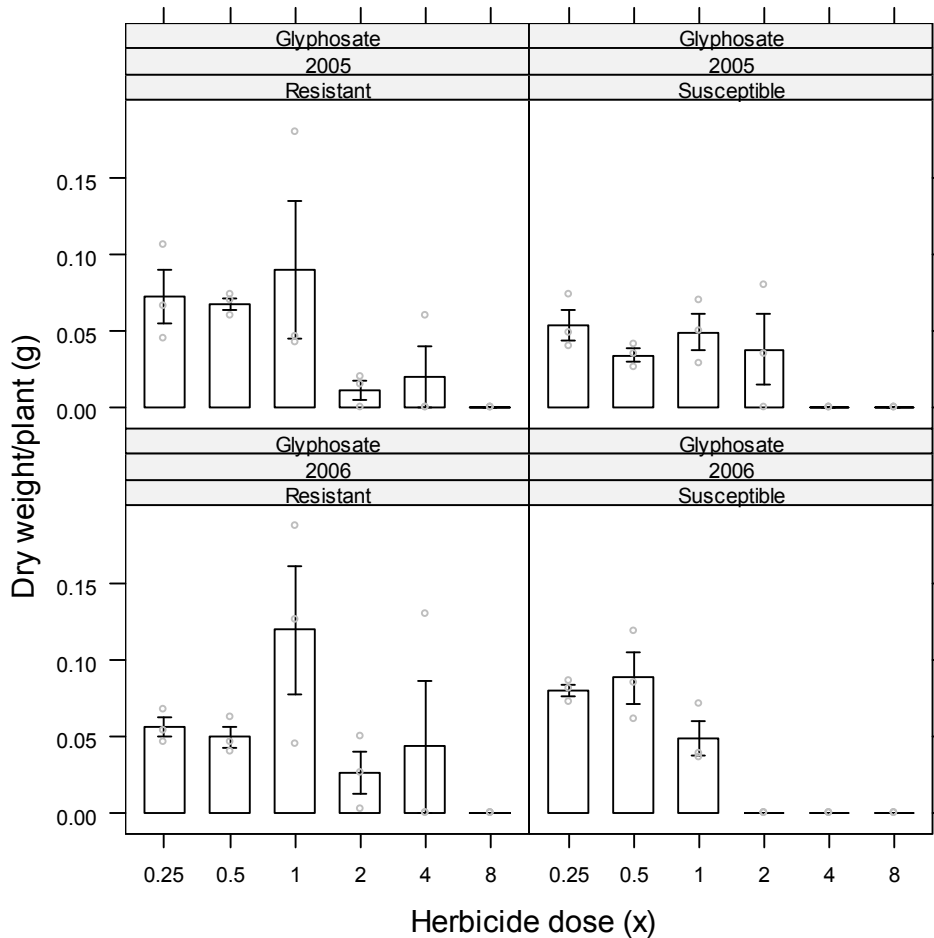


Figure 3.8 Effect of increasing doses of glyphosate on the average dry weight of glyphosate resistant and susceptible surviving *L. rigidum* seedlings. Vertical bars represent the mean dry weight at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

attained with the 4x and 8x doses. In 2006, plants sprayed with 2, 4 and 8x had similar low dry weight of weeds for the resistant sample and zero dry weights for all the 3 higher doses for the susceptible seed sample because there were no live seedlings remaining in each pot.

Sulfometuron

No *L. rigidum* seedlings sprayed with sulfometuron were recorded as live at any of the doses for the resistant seed samples during 2005 and 2006. Overall, marginally greater dry weight was achieved with the 2006 susceptible sample as compared with 2005 (Figure 3.9). There were no significant dose rate effects for the susceptible sample in either year.

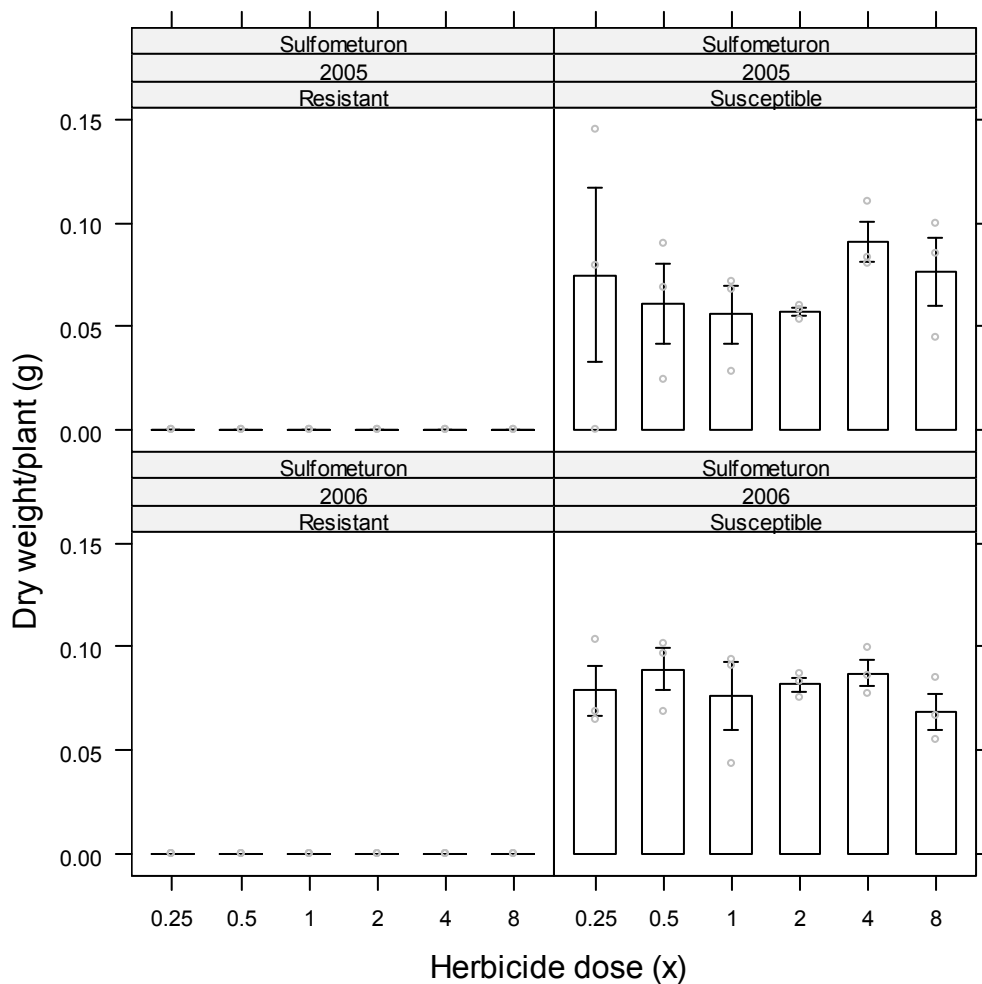


Figure 3.9 Effect of increasing doses of sulfometuron-methyl on the average dry weight of glyphosate resistant and susceptible surviving *L. rigidum* seedlings. Vertical bars represent the mean dry weight at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Tralkoxydim

On average, marginally higher weed dry weight was observed for the susceptible sample than the resistant sample in 2005 and higher in 2006 (Figure 3.10). Comparisons between the years indicate higher mean dry weight for both the resistant and the susceptible seed samples in 2005. During 2005, no plants survived at 8x the recommended dose rate and none of them survived at 4x and 8x the dose rate in 2006 for the resistant sample. There was no obvious dose response trend for the susceptible seed lot in either year.

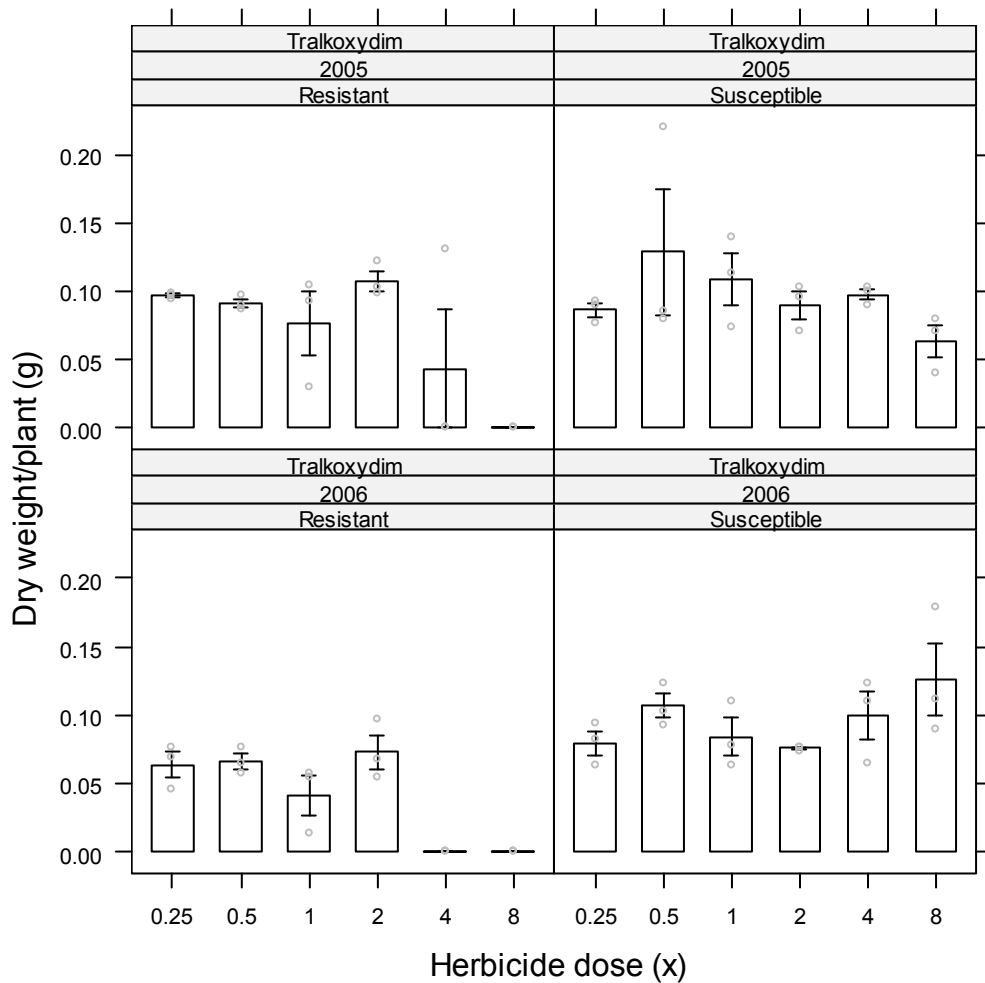


Figure 3.10 Effect of increasing doses of tralkoxydim on the average dry weight of glyphosate resistant and susceptible surviving *L. rigidum* seedlings. Vertical bars represent the mean dry weight at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Percent L. rigidum plants survived and regrown

Regrown plants were those *L. rigidum* seedlings which initially seemed to be dead after herbicide application but regrew later as abnormal small bushy plants. The survived plants

were assessed on the criteria defined by Llewellyn and Powles (2001). i.e. they showed no or very little injury as a result of the herbicide application at increasing doses. The % of *L. rigidum* plants survived or regrown as a proportion of total emerged were recorded at 21 DAS.

Results for the individual herbicide treatments are represented in separate graphs. The analysis of deviance showed that the four way, three way and two way interactions and the main terms were significant. The four way interaction of counts x seed x year x chemical was not significant ($P=0.298$).

Chlorsulfuron

At most of the increasing doses of chlorsulfuron for the susceptible sample, the % survival of *L. rigidum* plants per pot was generally higher than the resistant seed sample in both years (Figure 3.11). There were very few or nil % of susceptible plants that regrew compared with the resistant sample both in 2005 and 2006. There appeared to be regrowth occurring at all the doses of the resistant sample in both the years except at 1x in 2005. The survived plant population for the resistant seed sample declined as dose increased although the dose response was less clear for the survived populations of the susceptible seed sample during both years.

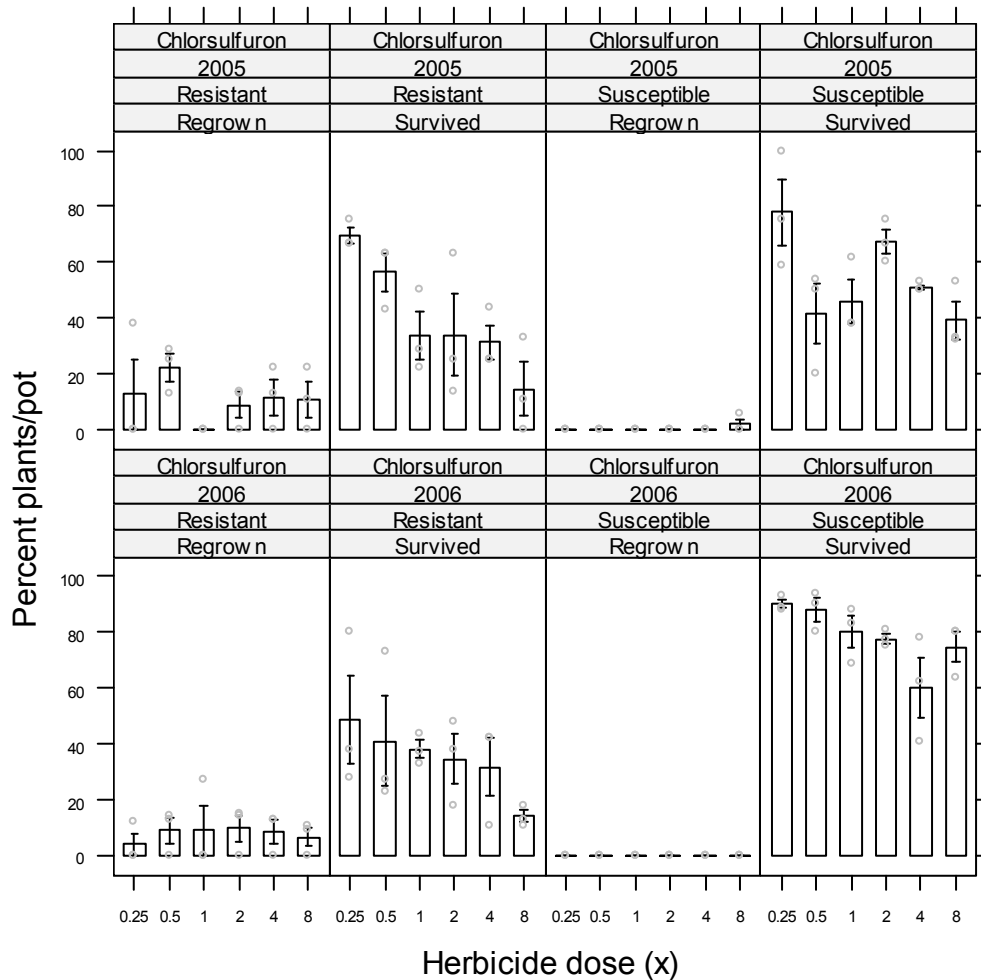


Figure 3.11 Effect of increasing doses of chlorsulfuron on the % survived and regrown *L. rigidum* plants at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Diclofop-methyl

In general, the percentage survival of susceptible *L. rigidum* plants per pot was higher than the resistant seed sample in both years at rates above 0.5x (Figure 3.12). The susceptible sample had a low % of regrown plants at 0.5 to 4x dose rate whereas with the resistant sample the regrowth of *L. rigidum* plants was observed only at 1x the recommended dose during 2005. At most of the doses, the level of survival for both the susceptible and resistant sample plants was higher in 2006 than in 2005. While % survival was reduced with increasing rate of diclofop-methyl in resistant plants, with zero survival at the 8x rate, a high proportion of susceptible plants survived diclofop-methyl application at all rates. Glyphosate resistant plants were more resistant but not enormously so when compared with so-called ‘susceptible’ population.

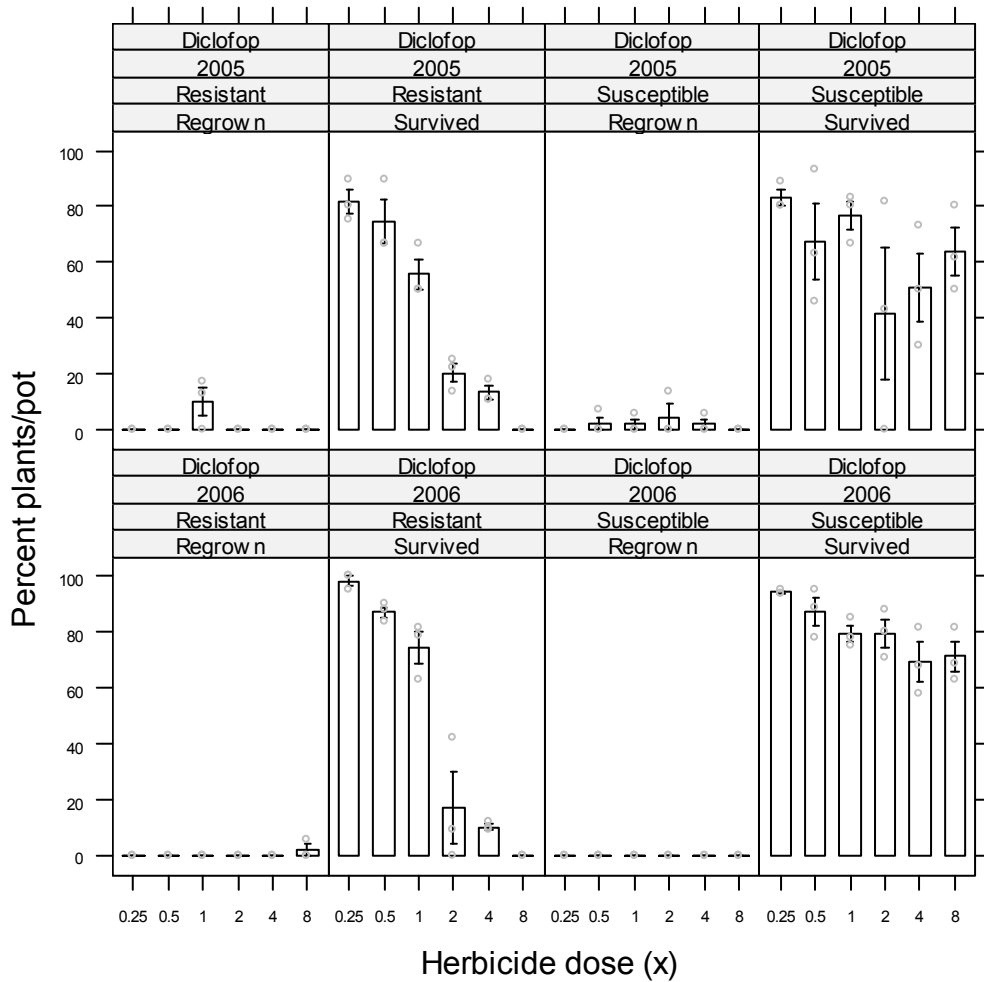


Figure 3.12 Effect of increasing doses of diclofop- methyl on the % survived and regrown *L. rigidum* plants at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Glyphosate

There were strong dose responses (higher the dose, lower the survival) recorded for all the treatment combinations for % survival of *L. rigidum* for both the glyphosate resistant and the susceptible seed samples during both years (Figure 3.13). The % survival for the resistant and susceptible seed samples during both years were generally higher compared with the regrown counterpart. Survival was greater in 2006 than 2005. In 2005, there was a large number of plants that regrew in both the seed samples with most occurring at the lower dose levels. More *L. rigidum* plants from the resistant population survived the recommended glyphosate rate (1x) than from the susceptible population and a relatively high % survived the 2x rate over both years, whereas only a small % from the susceptible population survived the 2x rate in 2005.

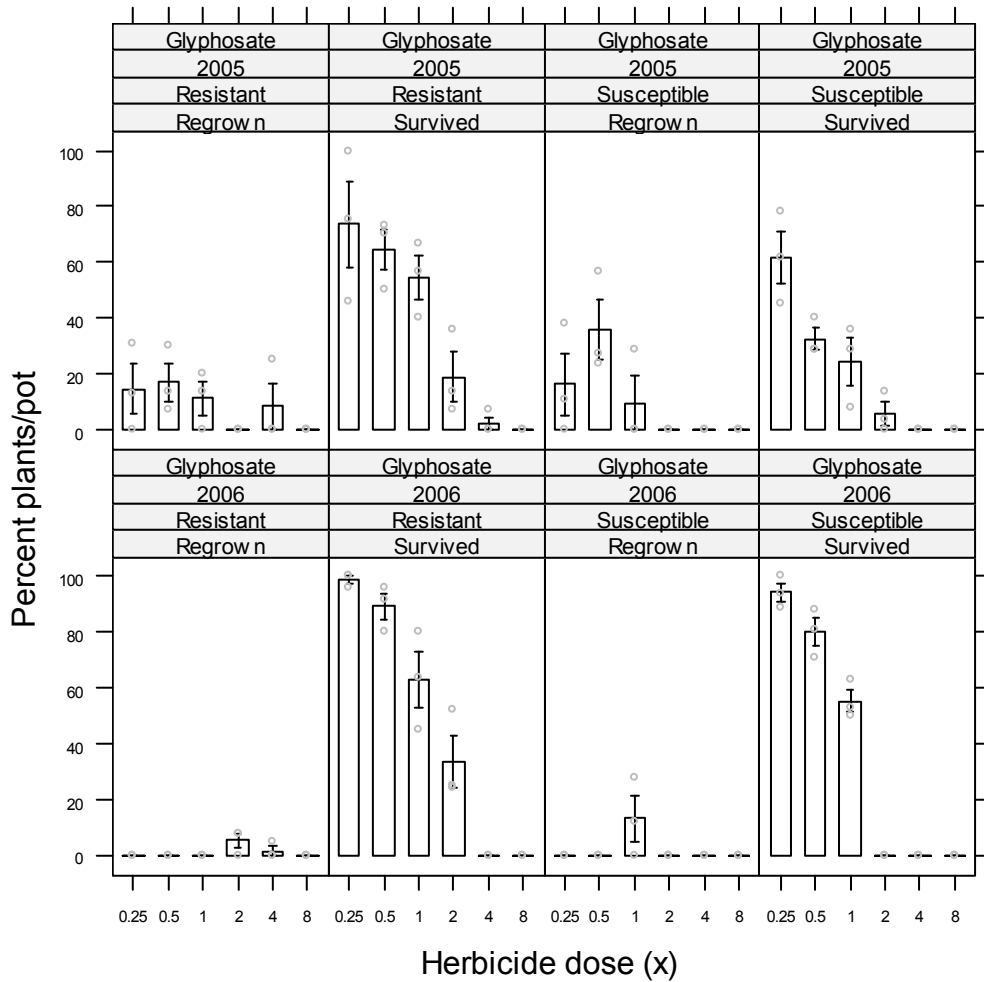


Figure 3.13 Effect of increasing doses of glyphosate on the % survived and regrown *L. rigidum* plants at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Sulfometuron

The seed sample resistant to glyphosate was entirely susceptible to all the doses of sulfometuron during both years (Figure 3.14). However, there was *L. rigidum* regrowth at most dose rates in the glyphosate susceptible seed sample during 2005 and in 2006, except at 0.25 and 0.5x doses, all other doses experienced regrowth. The % survival of *L. rigidum* in 2006 had a stronger dose response than in 2005 but in neither year did high dose rates achieve 100% *L. rigidum* control (Figure 3.14).

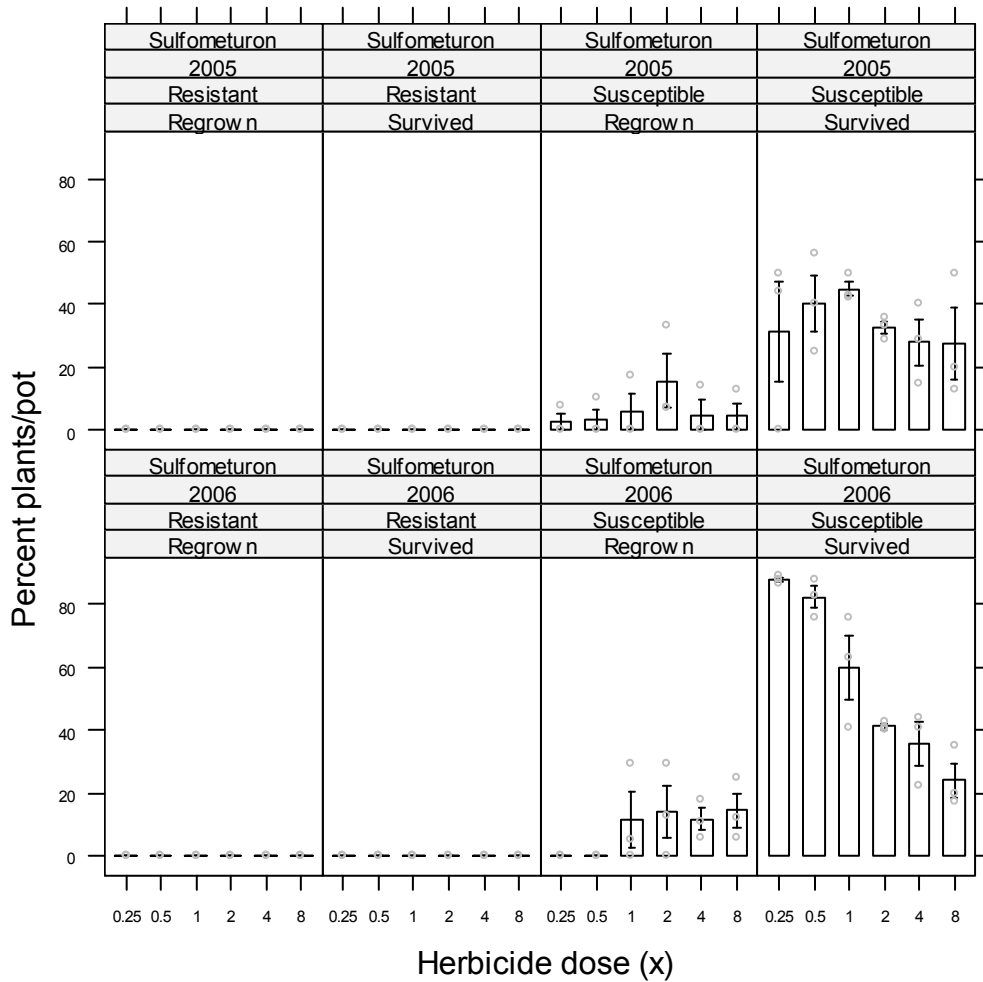


Figure 3.14 Effect of increasing doses of sulfometuron on the % survived and regrown *L. rigidum* plants at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Tralkoxydim

There were few plants that regrew in the tralkoxydim treatment. Increase in herbicide rate lead to a decrease in % survival for both seed types in both years (Figure 3.15). Glyphosate resistant seed samples were susceptible to tralkoxydim at higher doses (4x and 8x) in both the years but a relatively high proportion of susceptible plants survived at higher dose rates.

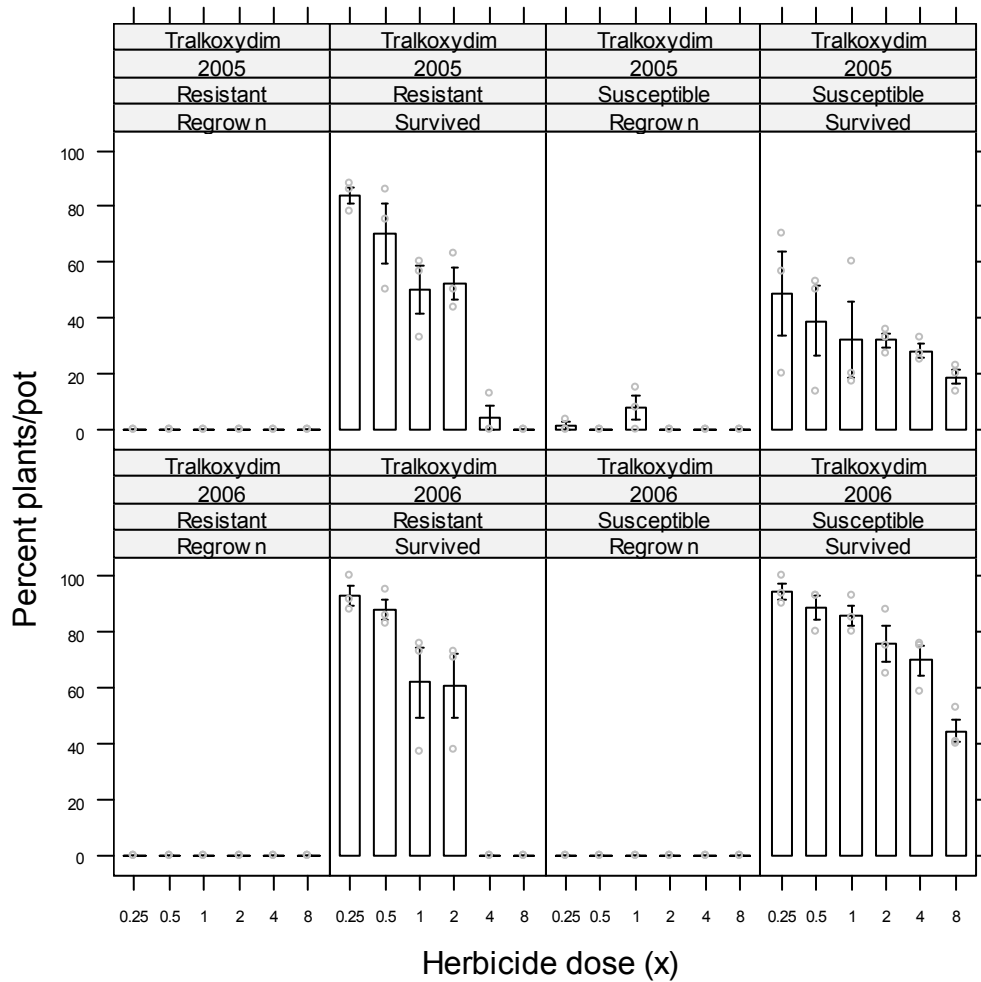


Figure 3.15 Effect of increasing doses of tralkoxydim on the % survived and regrown *L. rigidum* plants at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Resistance levels

Resistance levels were classified using the criteria as defined by Llewellyn and Powles (2001). The survived plants were the ones which showed no or very little injury as a result of the herbicide application at increasing doses. The populations of *L. rigidum* were classified as resistant if more than 20% of the plants survived the herbicide treatment (recommended rate). Populations in which 1 to 20% of plants survived were classified as developing resistance and those classified as susceptible were where all the plants were killed.

Chlorsulfuron

Both the susceptible and resistant seed samples of *L. rigidum* were resistant to chlorsulfuron at all the doses (Figure 3.16).

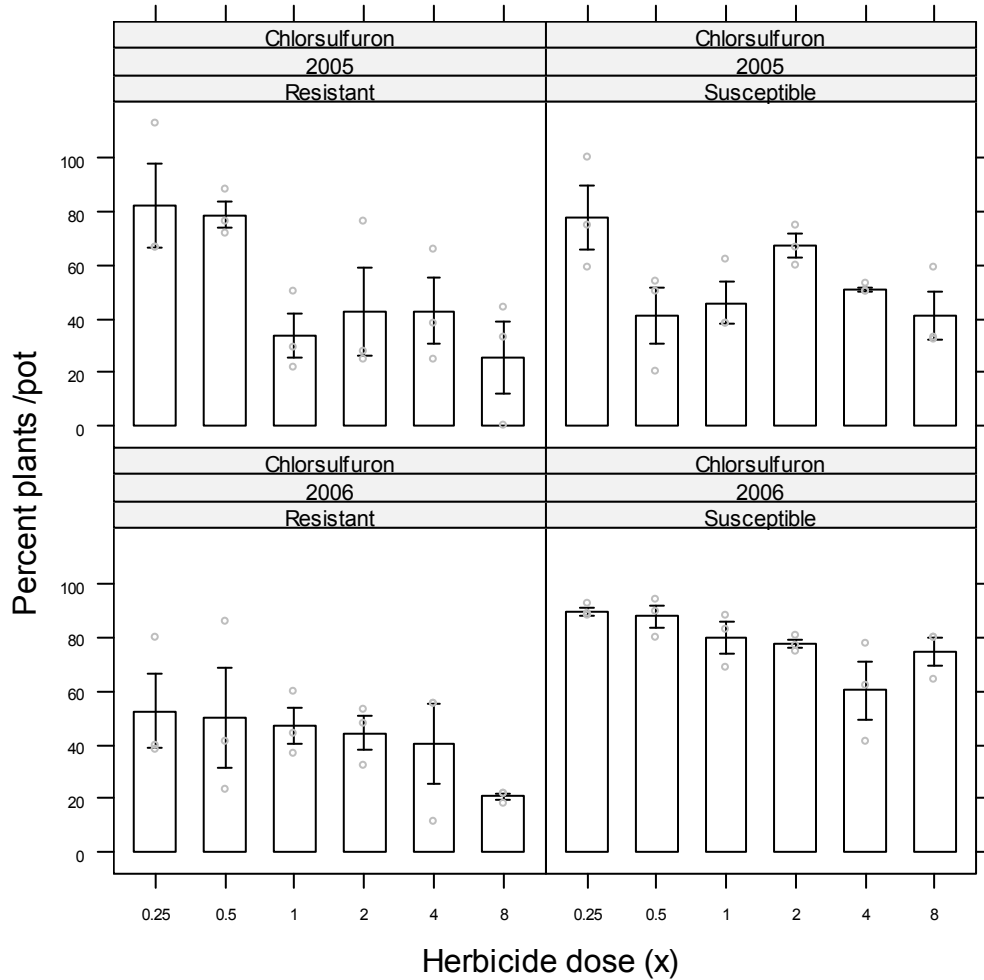


Figure 3.16 Effect of increasing doses of chlorsulfuron on the % total survival (survived + regrown) of *L. rigidum* seed samples at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Diclofop- methyl

Plants from the resistant seed sample were resistant to diclofop-methyl up to 2x the dosage rate and including the recommended rate and were thereafter developing resistance against this herbicide at levels up to 8x the dosage rate (Figure 3.17). Even at 8x rate there were some surviving plants across the 2 years so according to the criteria were developing resistance. Plants from the susceptible seed sample were resistant to diclofop-methyl at all the herbicide dose rates.

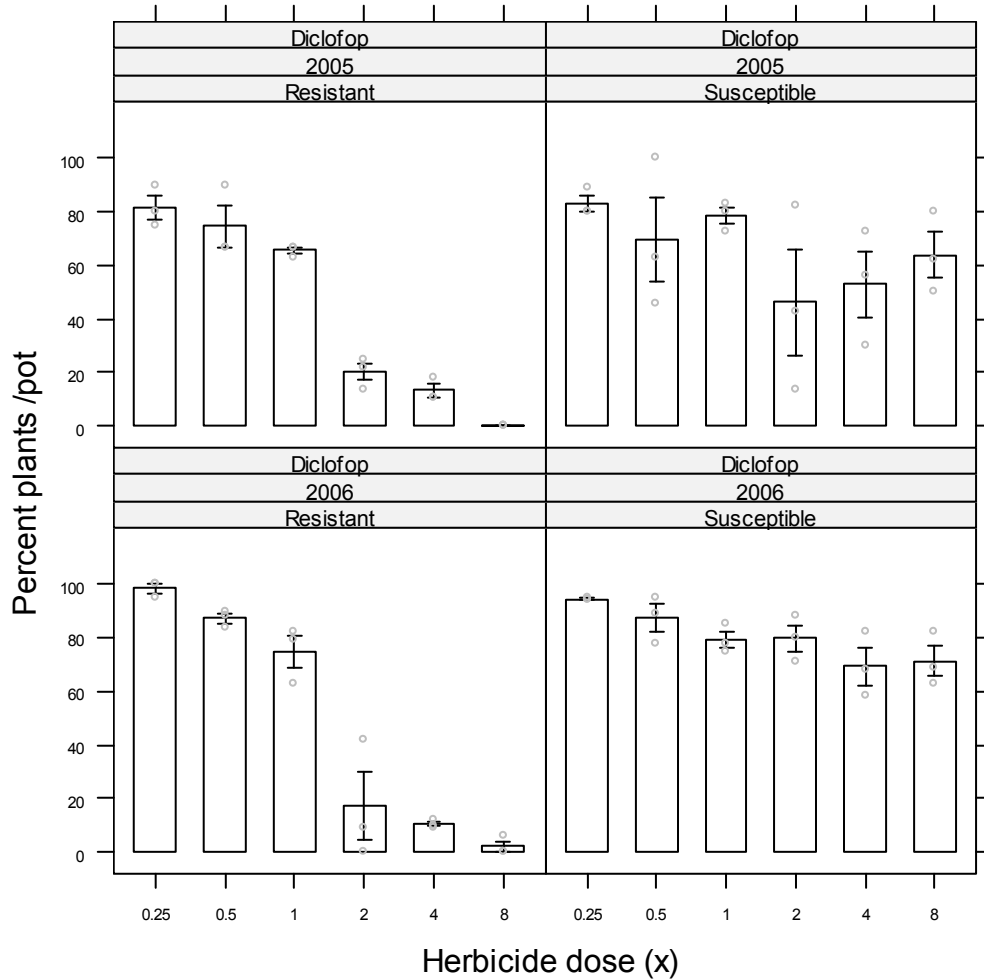


Figure 3.17 Effect of increasing doses of diclofop- methyl on the % total survival (survived + regrown) of *L. rigidum* seed samples at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Glyphosate

Lolium rigidum plants from the resistant seed sample were resistant to glyphosate up to 2x the recommended rate. The plants were also developing resistance to the 4x dose but were still susceptible to the 8x rate (Figure 3.18). For the susceptible seed sample, *L. rigidum* plants were resistant to glyphosate at up to the recommended rate (1x), were developing resistance to 2x the recommended rate but were still susceptible to 4x and 8x the glyphosate dose.

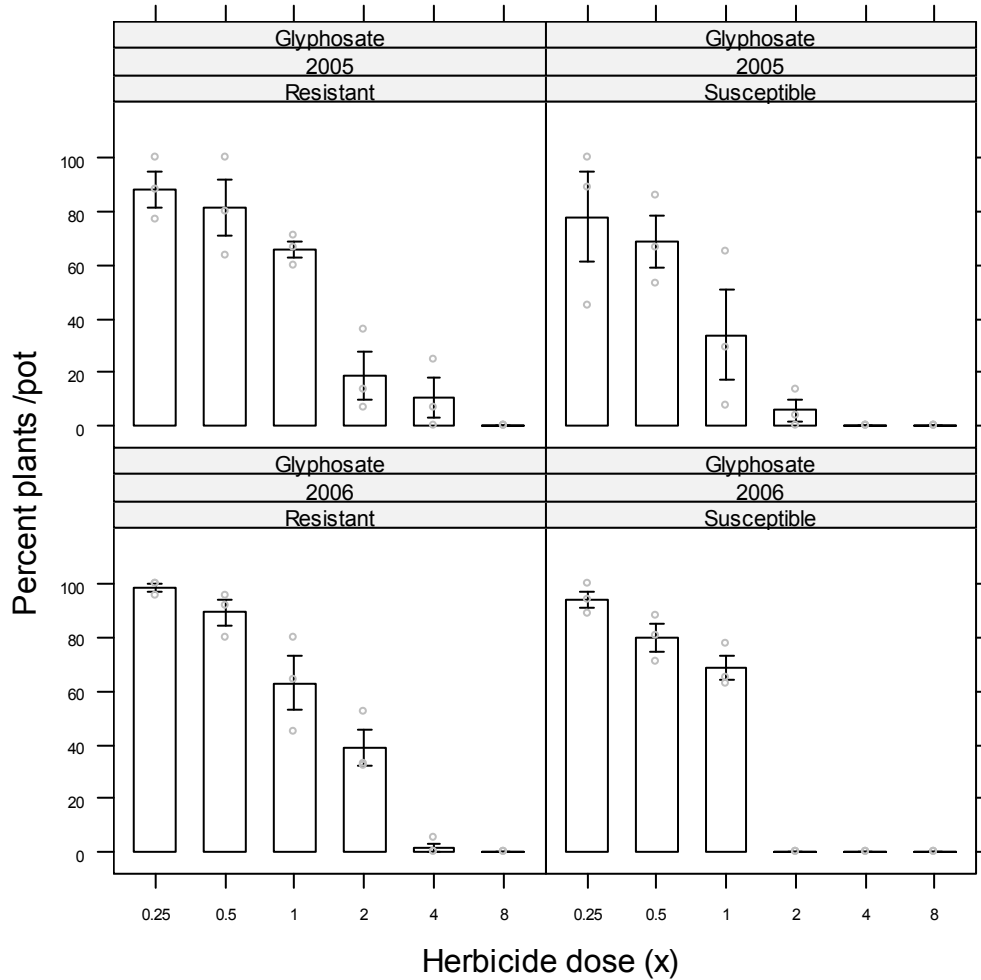


Figure 3.18 Effect of increasing doses of glyphosate on the % total survival (survived + regrown) of *L. rigidum* seed samples at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Sulfometuron

All the *L. rigidum* plants grown from the glyphosate resistant seed sample, were 100% susceptible to sulfometuron at all the doses even 0.25 and 0.5 the recommended rate (Figure 3.19), conversly, all the plants from the glyphosate susceptible seed sample were resistant to sulfometuron at all the doses.

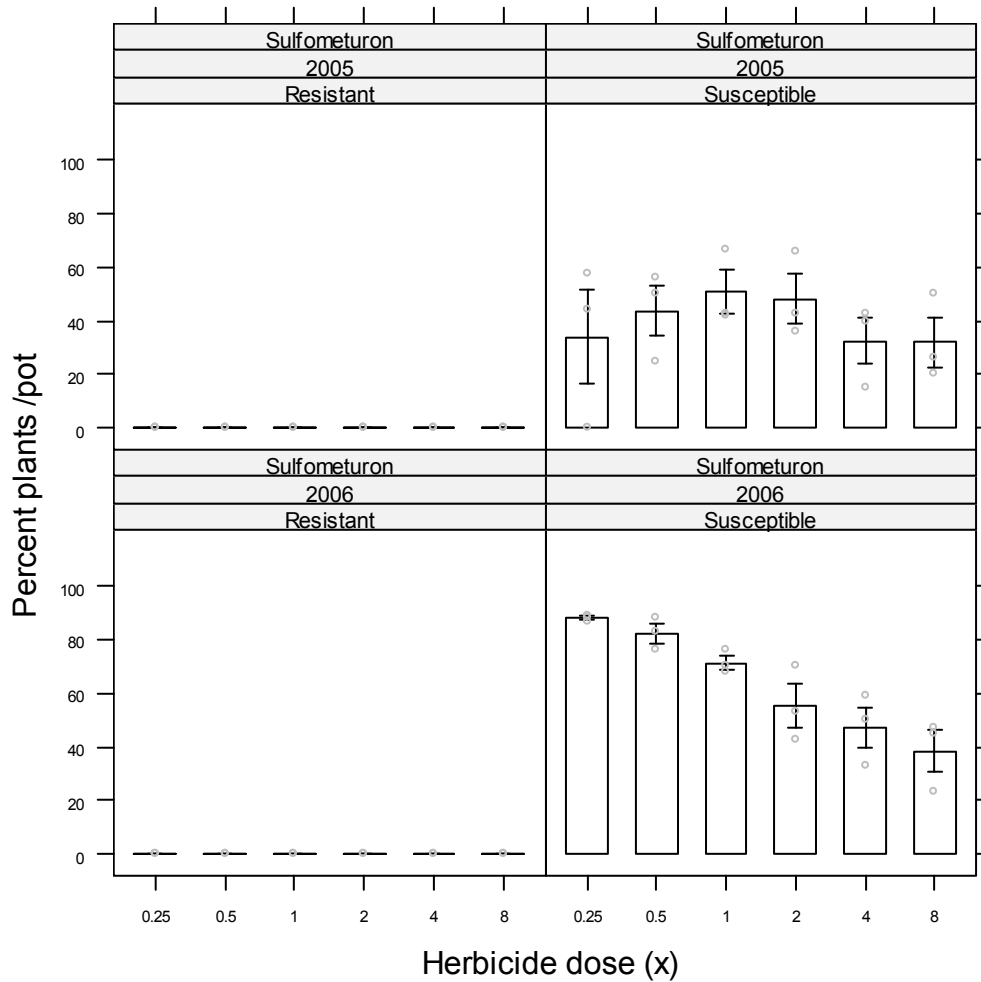


Figure 3.19 Effect of increasing doses of sulfometuron on the % total survival (survived + regrown) of *L. rigidum* seed samples at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

Tralkoxydim

Lolium rigidum plants from the resistant seed sample were resistant to tralkoxydim at rates up to 2x the recommended rate. The population was developing resistance to the 4x dose but was still susceptible to the 8x dose (Figure 3.20). Plants from the susceptible sample, on the other hand, were resistant to tralkoxydim at all doses.

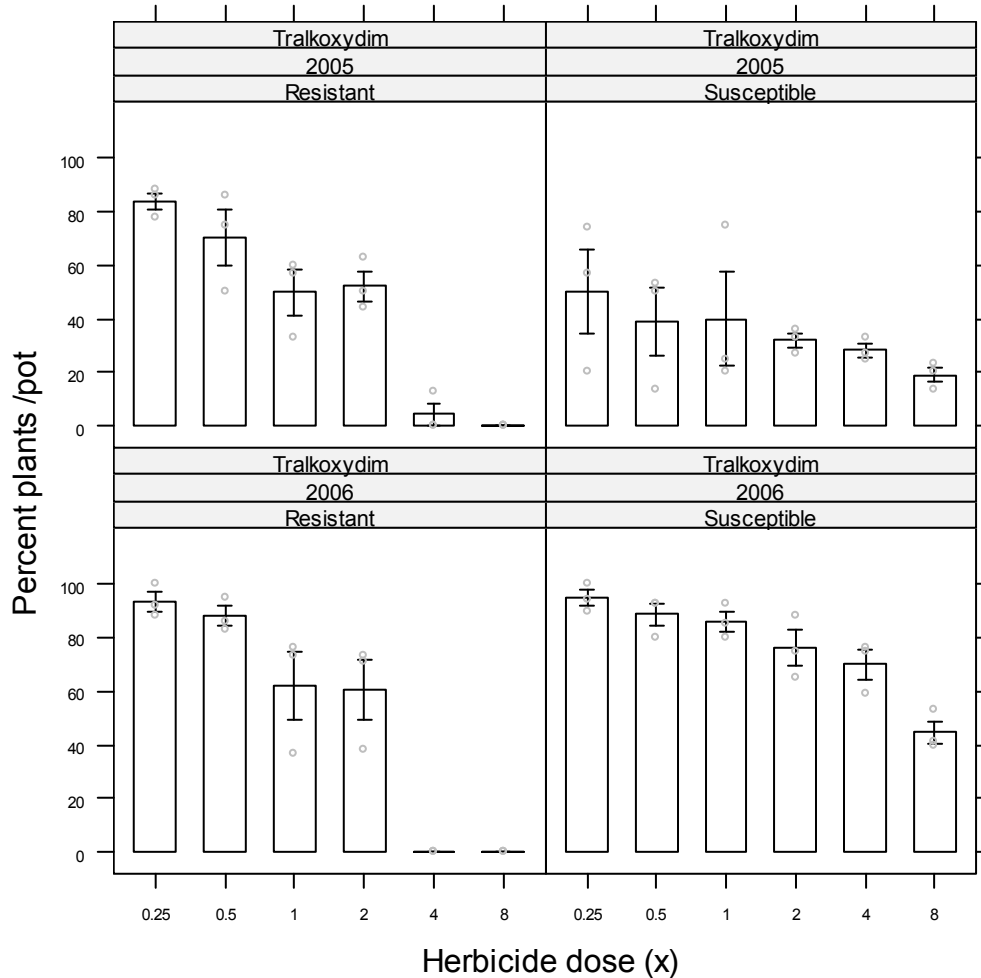


Figure 3.20 Effect of increasing doses of tralkoxydim on the % total survival (survived + regrown) of *L. rigidum* seed samples at 21 days after spraying. Vertical bars represent the % *L. rigidum* plants/pot at each dose level with a standard error bar (\pm). Hollow circles represent the replicate values of each treatment.

3.4. Discussion

The aim of the experiment was to assess the effectiveness of a range of commonly used herbicides on *L. rigidum* control and to determine levels of resistance already present in selected populations which could affect *L. rigidum* control.

Although it was thought that the locally purchased seed of *L. rigidum* would provide a useful comparison of seed that would be susceptible to glyphosate, it was found that it was also resistant to glyphosate up to the recommended rate of application and had multiple and/or cross resistance to all the other herbicides tested in this trial. This suggested that even in *L. rigidum* grown for pasture seed, glyphosate as well as several of the other herbicides were likely to have been used repeatedly and that seed being sold commercially,

with the potential to cross with weedy *L. rigidum*, is either developing or has already developed resistance to glyphosate as well as a range of other herbicides.

Grain and pasture growers in northern NSW need to select the appropriate herbicide for managing *L. rigidum* populations. The use of group AI herbicides across Australia and of group B herbicides in Western Australia and NSW is a high economic risk strategy unless it is supported by a resistance test on every species (Broster and Pratley 2006). The glyphosate resistant seed sample of *L. rigidum* obtained from the Liverpool Plains and the other sample available for sale locally (a product of Victorian pasturelands), showed some level of resistance to all the herbicides used in this trial (Table 3.2). Multiple and cross-resistance in *L. rigidum* has been well documented by Tardif *et al.* (1997). Llewellyn and Powles (2001) showed that 8% of diclofop-methyl-resistant populations were susceptible to chlorsulfuron, whereas 40% of chlorsulfuron-resistant populations were susceptible to diclofop-methyl. Similar results were reported by Gill (1995). Matthews (2002) found that the populations from South Australia surviving glyphosate had some resistance to ‘fop’ herbicides (Group A). More than 50% had high levels of resistance (greater than 30% survival to the fops) but only 10% had resistance to the ‘dims’ (Group A). Most populations had resistance to the group B herbicides usually at low to moderate levels (10-30% survival). Broster and Pratley (2006) confirmed high levels of resistance in *L. rigidum* to herbicides in group AI, AII and B. Higher levels (94%) have been found in Western Australia (Owen *et al.* 2005).

Table 3.2 Resistance levels recorded for resistant and the susceptible seed samples for all the herbicides and rates. x = Resistant, o = Developing resistance, - = Susceptible

Herbicide	Group	Resistant seed sample						Susceptible seed sample					
		Herbicide dose						Herbicide dose					
		0.25	0.5	1	2	4	8	0.25	0.5	1	2	4	8
Chlorsulfuron	B	x	x	x	x	x	x	x	x	x	x	X	x
Diclofop-methyl	A	x	x	x	o	o	o	x	x	x	x	X	x
Glyphosate	M	x	x	x	x	o	-	x	x	x	o	-	-
Sulfometuron	B	-	-	-	-	-	-	x	x	x	x	X	x
Tralkoxydim	A	x	x	x	x	o	-	x	x	x	x	X	x

From the five herbicides tested, only sulfometuron was capable of providing a substantial control of the glyphosate resistant populations collected from the Liverpool Plains. Anything less than 90% mortality due to herbicide application can be regarded as a commercial herbicide failure (Llewellyn and Powles 2001). During both the years at 21 DAS, sulfometuron was able to achieve 100% control of *L. rigidum* populations at all the doses probably because the glyphosate resistant seed sample had no previous application history of this herbicide. Nevertheless, Owen *et al.* found that almost 90% of *L. rigidum* populations contained individual plants with resistance to sulfometuron. The susceptible population was not effectively controlled by sulfometuron (Table 3.2). This population of *L. rigidum* was not only resistant to glyphosate but also to the group A herbicides diclofop-methyl and tralkoxydim (at either recommended or above recommended levels) and to the group B herbicide chlorsulfuron at all rates. Based on the present data and if this sample of *L. rigidum* seed is representative of other infestations of the weed in northern NSW, then farmers need to find alternatives such as herbicides with different modes of action or perhaps tank mixtures to which the weed is not resistant and to plan integrated weed management programs that incorporate non-chemical options (chapter 7) to achieve control of *L. rigidum*.

The dry weight of *L. rigidum* plants recorded at 21 DAS for chlorsulfuron, diclofop-methyl, glyphosate and sulfometuron largely corresponded to the % control achieved in most of the treatment combinations. However, in certain treatment combinations, the dry weight was higher than would be expected based on the greater % control achieved. The possible reason for this may be that in some pots, the survived *L. rigidum* plants grew robustly due to reduced competition with the death of other plants and as a result the dry weight with a higher % control was comparable with others having a lower % control.

Temperature differences may have played a role in affecting the efficacy of herbicides between years. Results obtained during 2006 show lower % control as compared with 2005 probably because temperatures in the glasshouse during the first year were 5°C higher than the second year. Powles *et al.* (1998) and Wakelin and Preston (2006) reported similar results of increase in % control with an increase in temperature. The % control increased from 7 to 21 days after spraying (DAS) for most of the herbicides and as a result, the greatest mortality was observed at 21 DAS, probably because the herbicide takes time to be completely absorbed and translocated in the plant system and cause injury.

3.5. Conclusions

The following major points concerning the effects of increasing doses of chlorsulfuron, diclofop-methyl, glyphosate, sulfometuron and tralkoxydim on the percent control, dry weight, % regrowth and resistance levels of glyphosate resistant and susceptible *L. rigidum* plants came out of this study.

- The *L. rigidum* population originating from the Liverpool Plains and considered to be resistant to glyphosate had also developed strong resistance levels against chlorsulfuron, diclofop-methyl and tralkoxydim. However, this individual population was able to be effectively managed with the use of sulfometuron. The other sample originating from Victoria and considered as susceptible to glyphosate was not only found highly resistant to chlorsulfuron, diclofop-methyl, tralkoxydim and sulfometuron but also to glyphosate. It appears from the results that these populations possess both cross and multiple resistance.

- These findings strongly suggest that the grain growers on the Liverpool Plains should limit their use of herbicides to those to which these populations are not resistant (ideally those with alternative modes of action) as well as applying alternative integrated weed management options to control *L. rigidum* (see chapter 7). Also, graziers and mixed farmers should be warned about *L. rigidum* seed purchases as this may spread resistance to other areas previously not infested.

Chapter 4. Characterisation and monitoring of seedbanks

4.1. Introduction

A soil seedbank has been defined as containing those seeds that can remain dormant for a period of time in the surface soil until their germination is triggered by an environmental change (Archibold 1989, Simpson *et al.* 1989). Buried weed seeds are an important component of weed populations since they are largely responsible for the perpetuation of weeds in cropping systems (Ball and Miller 1990, Cardina *et al.* 1991, Yenish *et al.* 1992). This has given rise to the concept that management of seedbanks is needed to give long term control of weeds (Wilson *et al.* 1985). A basic understanding of seedbank ecology of annual weeds may permit farm managers to implement standard farming practices (e.g. seedbed preparation) at times that (1) optimize mechanical weed control and crop yields, (2) lower agrichemical use and input cost and (3) increase profits (Forcella *et al.* 1993b). A knowledge of the levels and content of the weed seedbank is very important because it provides evidence of past field management and may allow forecasts concerning future weed problems (Forcella 1992, Wilson *et al.* 1985). Accurate prediction of future weed problems based on samples of seed rain or soil seedbank could assist managers in planning appropriate control measures (Buhler *et al.* 1997, Cardina and Sparrow 1996, Sagar and Mortimer 1976).

Characterisation of the long-term effect of agricultural management systems on weed communities will aid in developing sustainable weed management practices (Davis *et al.* 2005). One of the fundamental challenges for improving weed management is to determine whether the information stored in the weed seedbank can help predict the nature of future weed infestations and effects on crop yields (Buhler *et al.* 1997, Cardina and Sparrow 1996, Wilson *et al.* 1985). The density and species composition of below- and aboveground components of weed communities vary both in the response to underlying environmental variation (Albrecht and Auerswald 2003, Dieleman *et al.* 2000) and to shifts in agricultural management practices such as tillage (Anderson *et al.* 1998, Ball 1992, Buhler 1995, Clements *et al.* 1996, Dorado *et al.* 1999, Tuesca *et al.* 2001), crop rotation (Cardina and Herms 2002, Cardina *et al.* 1998, Moonen and Barberi 2004) and weed management (Barberi *et al.* 1998, Mayor and Dessaint 1998, Menalled *et al.* 2001). Weed seedbank population density also varies with different years and with the time of soil sampling (Felix and Owen 2001). Monitoring of weed seedbank changes over time has

long been considered as an important means to review the altering pattern of weed species populations over time (Schweizer *et al.* 1998).

In Australia competition from herbicide resistant *Lolium rigidum* is a serious economic consideration in cereal production areas, including on the Liverpool Plains region of northern New South Wales. Herbicide resistant populations have been reported at a range of locations and sites in this area (Storrie and Cook 2002). Confirmation of a sudden appearance of glyphosate resistant *L. rigidum* populations is posing a serious threat to the grains industry. Several other weeds also have either acquired or are at the threshold of acquiring resistance to one or more herbicides due to repeated use of the same herbicides year after year. Very little is known about the current status of weed seedbanks, including *L. rigidum*, on the Liverpool Plains. The aim of this study was to characterise and monitor *L. rigidum* and other weed species seedbanks on several representative farms on the Liverpool Plains to provide insights into changing seedbank dynamics over time with a range of management practices.

4.2. Methods

Sites

Sites with a history of glyphosate resistance in *L. rigidum* were selected on the Liverpool Plains in northern New South Wales which had a range of farm management practices including different tillage practices, crop rotations and spraying regimes.

Four properties (sites) were selected for sampling and either 3 or 4 paddocks were sampled from each site where *L. rigidum* was known to occur. The properties were:

- Betoota (BT): Premer, four paddocks (S 31°28'02.5" E 149° 55' 52.4");
- Wheel Barrow Back (WB): Spring Ridge, three paddocks (S 31° 26' 27.3" E 149° 59' 57.4");
- Tamarang (TAM): The Point, three paddocks (S 31°29' 33.8" E 150° 05'33.8");
and
- Bundella (BUN): Premer, four paddocks (S 31°35' 02.4" E 150° 00' 04.5").

All these properties were located within a 20 km radius.

Sampling

The soil sampling for seedbank studies occurred from 2004 to 2006. In 2004, samples were collected from the paddocks in the first week of June after most of the *L. rigidum* and other weed seedlings had already emerged. In 2005 and 2006, samples were taken earlier in the first week of May before germination of the winter weeds had occurred and before winter crops had been sown. Soil samples were taken from predominantly zero tilled and a few cultivated fields (Figure 4.1). Soil sampling for soil type assessment for each paddock was assessed during 2004 before initiation of sampling for seedbank studies. Four samples (pseudo replicates) from each paddock were sampled from 10 m in from one corner of the field. Soil was bulked and sent to a commercial laboratory for analysis.



Figure 4.1 Soil sampling by the author as on the Liverpool Plains.

Surface soil study

In each paddock, soil samples were taken along four 50 m replicate transects at 1 m intervals giving a total of 50 cores per replicate, which were bulked, with a total of 200 cores from each paddock. Transects were located 10 m apart and started 15 m in from the edge of the field (Figure 4.2). Individual soil cores were 2.5 cm in diameter and 10 cm depth. The samples were placed in plastic bags and kept in large ice boxes in the field and then transferred to a cool room at 4°C until germinated.

Depth studies

From each site, one paddock was selected from 3 or 4 paddocks sampled for surface studies. The paddocks used for depth studies at each of the sites were paddock 4 at BT,

paddock 2 at WB, paddock 1 at TAM and paddock 3 at BUN. In each paddock, soil samples were taken along four 45 m replicate transects at 15 m intervals at four different depths in a square of 20 x 20 cm and bulked for each replicate. Transects were located 10 m apart and started 15 m in from the edge of the field. Individual soil samples were taken from 0-2, 2-5, 5-10 and 10-15 cm depth with the help of shovel marked with all the four depths. The samples were processed in a similar way to that for the surface soil studies.

Global Positioning System (GPS) recordings were used to mark the exact location of the four corners of the sampling area to ensure that soil samples were taken from the same place each year. This allowed an assessment of the changes in the seed banks over time.

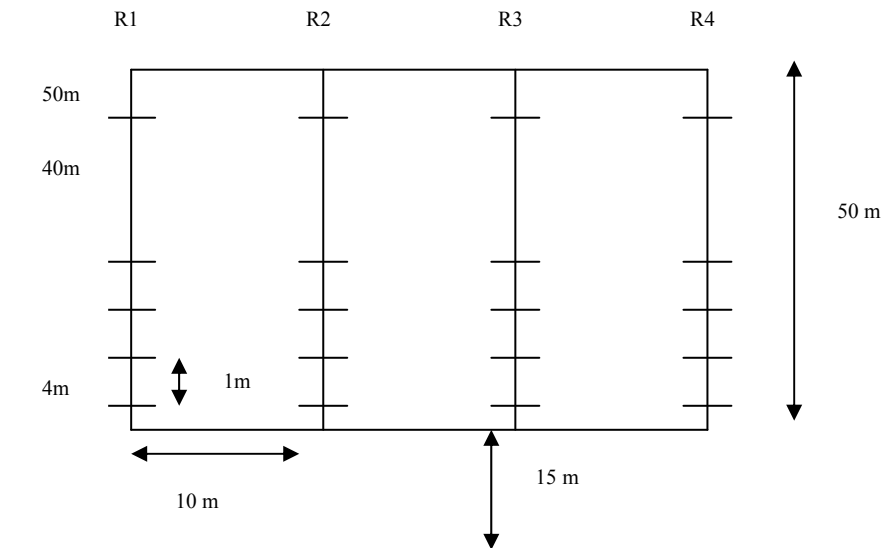


Figure 4.2 Diagrammatic representation of sampling procedure.

Germination

Seed germination from soil samples was assessed using 36 x 20 cm plastic trays on wire mesh tables inside a polyhouse 2 weeks after sampling from the field. A paper towel folded twice was placed at the base of the trays and then the soil filled in each tray to a depth of approximately 5 cm. Trays were watered as and when required to keep the soil moist. Temperatures inside the polyhouse ranged from 2°C - 12°C minimum to 13°C – 42°C maximum. Seedlings were identified using Wilson *et al.* (1995), Wilding *et al.* (1993) and Moerkerk and Barnett (1998) and counted as and when the weeds emerged. They were then uprooted. After 3 months allowed for germination, the samples were air dried for one week. Thereafter the samples were inverted, mixed and again settled in the trays and

watered to allow for further germination as per Forcella *et al.* (2003) (Figure 4.3). The total weed emergence in each tray was converted to a per meter squared (m^{-2}) basis of the original field sampling based on the area and number of cores from each replicate. Cropping and farm management histories for the sampled paddocks were obtained from individual farmers through face to face interviews and written responses.



Figure 4.3 Watering of germination trays in the polyhouse

Data analysis

Given the relatively small number of properties with known glyphosate resistant *L. rigidum* populations on the Liverpool plains at the start of this trial and the relatively large number of site specific variables influencing seedbanks, it was not possible to set up structured comparisons that were amenable to comparative or factorial analysis using, for example, t-tests or ANOVA. The data were collected to characterise seedbanks (species and numbers) on a range of properties where glyphosate resistant *L. rigidum* had recently appeared and to follow changes in these seedbanks over time. Means of the four replicates (pseudoreplicates) and their standard errors are therefore presented for each species in each of the paddocks on each of the four properties over the 3 years of sampling, and these data are discussed in the text.

4.3. Results

Management practices, specifically the crop rotations performed by the farmers, varied considerably between paddocks and sites. The cropping histories provided by the farmers indicated that glyphosate was being sprayed 3-4 times when the field was being kept

fallow and once before sowing the crop in both winter and summer. Various other selective herbicides were also being sprayed for broad leaf and grassy weeds other than *L. rigidum*. The persistent seedbanks of *L. rigidum* may indicate the presence of herbicide resistance.

The results presented are on the basis of seedbanks of various weeds present in the soil regardless of the control provided by individual herbicides and the dormancy characteristics present during the time of germination and emergence in the polyhouse. Due to the late sampling in 2004, many of the paddocks in that year had low or zero emergence counts because seeds had germinated in the field.

Surface soil seed banks

There were large variations between sites (properties) and between individual paddocks within sites in the number of seedlings that emerged for different weed species. There were 17 weed species recorded in total but four of these had negligible counts and hence were discarded. These were *Rumex* spp., *Convolvulus arvensis*, *Medicago lupulina* and *Solanum nigrum*. In the 3 years the emerging weed species were similar. The 13 remaining species were *Fumaria parviflora*, *Cyclosporum leptophyllum*, *Sonchus oleraceus*, *Gamochaeta pennsylvanica*, *Veronica arvensis*, *Anagallis arvensis*, *Melilotus indica*, *Lolium rigidum*, *Polygonum aviculare*, *Lamium amplexicaule*, *Poa* spp., other grass spp. and *Crassula colorata*. Results have been presented for all except *F. parviflora*, *C. leptophyllum*, *V. arvensis* and *A. arvensis* which had low and variable counts in the 3 years of sampling.

Lolium rigidum, *P. aviculare* and *L. amplexicaule*

At BT, there was only one paddock with a low level of *L. rigidum* emergence in 2004 (Table 4.1), potentially due to sampling after weeds had already emerged. In 2005, soil from paddock 2 had a large number of germinating *L. rigidum* plants (1507 m⁻²) which decreased strongly in 2006; paddock 1 had fewer emergences despite a similar rotation and tillage practice to nearby paddock, which had none. In 2006, total emergence declined strongly in paddocks 1 and 3 and paddock 4 still had few emergences. *Polygonum aviculare* had low emergence counts in most of the paddocks in 2004 and 2006. In 2005 greater numbers emerged in paddocks 1, 3 and 4 and the numbers increased in paddock 4 in 2006. Emergence of *L. amplexicaule* drastically increased from 2004 to 2005 in paddock 4 with others ending up with nil emergences.

At WB, no *L. rigidum* plants emerged in two of the three paddocks and emergence declined from 2004 to 2005 and was nil in 2006 in paddocks 1 and 2. *Polygonum aviculare* also did not emerge in two of the three paddocks during the 3 years of sampling with greatest counts in 2006 in paddock 2 (132 m⁻²). Overall, the numbers increased in paddock 2 and decreased in paddock 3 in 2006. There were large numbers of *L. amplexicaule* in two of the three paddocks in 2005 and 2006. The numbers gradually increased over the years in paddock 1 and 2 and decreased in paddock 3 (Table 4.1).

At TAM, there was no emergence of *L. rigidum* in 2004 and 2006 and low emergence in 2005 in all 3 paddocks (Table 4.1). Year 2004 and 2006 were associated with lower counts of *P. aviculare* in paddock 2 and nil in others. There were low emergences in 2005 in all the 3 paddocks. The population increased in paddock 2 over 2005 and 2006. *Lamium amplexicaule* emerged in relatively high numbers in 2004 in all 3 paddocks and subsequently showed drastic increase in numbers in 2005 and thereafter a decrease in numbers during the 2006 sampling.

Paddocks 1 and 2 in 2004 and 1, 2 and 3 in 2005 at BUN were associated with higher *L. rigidum* numbers with no emergence observed in 2006. The populations increased in paddock 2 over the first 2 years. *Polygonum aviculare* had few or no germinations in 2004 and 2005 with larger numbers in 2006 in three of the four paddocks (Table 4.1). *Lamium amplexicaule* had low emergence in three of the four paddocks in 2004 and nil emergence in 2006. There were higher numbers in 2005 compared with 2004 in the first three paddocks. The populations increased in paddocks 1, 2 and 3 during the first 2 years followed by nil emergence in the final year of sampling.

Crassula colorata and Poa and other grass spp.

At all the four properties, there was no emergence of any of the *Poa* spp., grass spp. and *C. colorata* in 2005 and 2006, except in paddock 2 in 2005 and 1 and 2 in 2006 at WB where there were high numbers of *C. colorata* (Table 4.2). The first year of sampling showed variable levels of emergence at different sites and paddocks. There were relatively small emergences of *Poa* spp. in only one of the four paddocks at BT and BUN, and WB and TAM had higher numbers in 2 of the paddocks. Grass spp. were prevalent at a single paddock only at BT, TAM and BUN. Wheel Barrow Back had comparatively greater numbers in 2 of the 3 paddocks. There was no *C. colorata* at TAM, BUN and BT whereas

WB was associated with higher emergence in paddocks 2 and 3. Paddock 2 had especially high levels of *C. colorata* in 2004.

Table 4.1 Numbers of seedlings (m⁻²) emerging from seedbanks for individual weeds in 2004, 2005 and 2006 at different sites and paddocks on the Liverpool Plains in northern NSW (surface soil study).

PR	P	Soil	Tillage			2003 crops		2004 crops		2005 crops		<i>L. rigidum</i>			<i>P. aviculare</i>			<i>L. amplexicaule</i>		
			04	05	06	W	S	W	S	W	S	04	05	06	04	05	06	04	05	06
BT	1	GMC	NT	NT	NT	WH	F	F	SO	F	SO	-	62 ± 35	-	-	42 ± 29	-	-	-	-
BT	2	GMC	NT	NT	NT	B	F	F	SO	F	SO	-	1507 ± 157	-	-	-	-	-	-	-
BT	3	GMC	NT	NT	NT	WH	F	F	SO	F	SO	-	-	-	10 ± 10	42 ± 29	-	-	-	-
BT	4	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	31 ± 31	-	31 ± 31	10 ± 10	31 ± 31	51 ± 51	10 ± 10	143 ± 117	-
WB	1	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	-	-	-	-	-	-	204 ± 83
WB	2	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	41 ± 31	31 ± 31	-	41 ± 29	-	132 ± 67	51 ± 51	236 ± 64	285 ± 232
WB	3	BMC	CU	NT	NT	WH	SO	D.W	F	WH	F	-	-	10 ± 10	-	72 ± 42	-	-	226 ± 68	-
TAM	1	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	31 ± 31	-	-	21 ± 12	-	41 ± 17	502 ± 229	326 ± 95
TAM	2	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	52 ± 31	-	10 ± 10	72 ± 59	51 ± 25	41 ± 0	175 ± 4	10 ± 10
TAM	3	GBMC	NT	NT	NT	F	SO	F	SO	F	SF	-	10 ± 10	-	-	31 ± 20	-	214 ± 3	2391 ± 437	265 ± 203
BUN	1	BMC	CU	NT	NT	WH	SO	F	SO	F	SO	10 ± 10	10 ± 10	-	10 ± 10	-	-	-	83 ± 45	-
BUN	2	BMC	CU	NT	NT	WH	SO	F	SO	F	SO	479 ± 69	502 ± 82	-	-	52 ± 31	-	51 ± 20	136 ± 11	-
BUN	3	BMC	NT	NT	NT	F	SO	WH	SO	F	SO	-	42 ± 42	-	-	10 ± 10	-	10 ± 10	41 ± 24	-
BUN	4	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	21 ± 12	-	10 ± 10	10 ± 10	-

T = Betoota, WB = Wheel Barrow Back, TAM = Tamarang, BUN = Bundella, PR = Property, P = Paddock, NT = No-Tillage, CU = Cultivated, W = Winter crop, S = Summer crop, WH = Wheat, SO = Sorghum, F = Fallow, CO = Cowpea, L = Lucerne, L&P = Lucerne and *Phalaris*, D.W. = Durum Wheat, B = Barley, CA = Canola, SF = Sunflower, T = *Triticale*, CG = Cattle grazing, - = No weeds, GMC = Grey medium clay, BSL = Brown sandy loam, GBMC = Grey brown medium clay, BMC = Brown medium clay

Sonchus oleraceus, *M. indica* and *G. pensylvanica*

All three weeds viz. *S. oleraceus*, *M. indica* and *G. pensylvanica* had low and variable counts across the properties and paddocks (Table 4.3). Year 2004 had low or nil emergences across all the properties. In 2005, two of the four paddocks at BT had relatively higher numbers of *S. oleraceus* with little or no emergence on the remaining properties. BT and BUN had nil emergence of *S. oleraceus* in 2006 and TAM had low emergence in two of the three paddocks whereas WB had higher numbers in the first two paddocks. *Melilotus indica* had nil emergence on most of the properties during 2005 and 2006. Paddock 3 at TAM was associated with higher numbers of *M. indica* in the first year and nil numbers thereafter, and three of the four paddocks at BT had low emergence. *Gamochaeta pensylvanica* showed a similar effect to *M. indica* with low emergence in one of the paddocks at BT, WB and TAM and nil at BUN.

Table 4.2 Numbers of seedlings (m⁻²) emerging from seedbanks for individual weeds in 2004, 2005 and 2006 at different sites and paddocks on the Liverpool Plains in northern NSW (surface soil study)

PR	P	Soil	Tillage			2003 crops		2004 crops		2005 crops		<i>Poa</i> spp.			Other grass spp.			<i>C. colorata</i>			
			04	05	06	W	S	W	S	W	S	04	05	06	04	05	06	04	05	06	
BT	1	GMC	NT	NT	NT	WH	F	F	SO	F	SO	-	-	-	-	-	-	-	-	-	-
BT	2	GMC	NT	NT	NT	B	F	F	SO	F	SO	-	-	-	-	-	-	-	-	-	-
BT	3	GMC	NT	NT	NT	WH	F	F	SO	F	SO	-	-	-	-	-	-	-	-	-	-
BT	4	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	20 ± 12	-	-	10 ± 10	-	-	20 ± 20	-	-	-
WB	1	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	530 ± 159	-	-	31 ± 20	-	-	285 ± 232	-	-	387 ± 131
WB	2	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	367 ± 303	-	-	61 ± 39	-	-	1110 ± 224	1099 ± 578	-	255 ± 39
WB	3	BMC	CU	NT	NT	WH	SO	D.W	F	WH	F	-	-	-	-	-	-	-	-	-	-
TAM	1	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	-	-	-	-	-	-	-	-	-
TAM	2	GBMC	CU	NT	NT	F	SO	F	CA	T	F	10 ± 10	-	-	10 ± 10	-	-	-	-	-	-
TAM	3	GBMC	NT	NT	NT	F	SO	F	SO	F	SF	112 ± 65	-	-	-	-	-	-	-	-	-
BUN	1	BMC	CU	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-	-
BUN	2	BMC	CU	NT	NT	WH	SO	F	SO	F	SO	41 ± 41	-	-	20 ± 20	-	-	-	-	-	-
BUN	3	BMC	NT	NT	NT	F	SO	WH	SO	F	SO	-	-	-	-	-	-	-	-	-	-
BUN	4	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-	-

BT = Betoota, WB = Wheel Barrow Back, TAM = Tamarang, BUN = Bundella, PR = Property, P = Paddock, NT = No-Tillage, CU = Cultivated, W = Winter crop, S = Summer crop, WH = Wheat, SO = Sorghum, F = Fallow, CO = Cowpea, L = Lucerne, L&P = Lucerne and *Phalaris*, D.W. = Durum Wheat, B = Barley, CA = Canola, SF = Sunflower, T = *Triticale*, CG = Cattle grazing, - = No weeds, GMC = Grey medium clay, BSL = Brown sandy loam, GBMC = Grey brown medium clay, BMC = Brown medium clay

Table 4.3 Numbers of seedlings (m⁻²) emerging from seedbanks for individual weeds in 2004, 2005 and 2006 at different sites and paddocks on the Liverpool Plains in northern NSW (surface soil study)

PR	P	Soil	Tillage			2003 crops		2004 crops		2005 crops		<i>S. oleraceus</i>			<i>M. indica</i>			<i>G. pennsylvanica</i>		
			04	05	06	W	S	W	S	W	S	04	05	06	04	05	06	04	05	06
BT	1	GMC	NT	NT	NT	WH	F	F	SO	F	SO	-	-	-	20 ± 20	-	-	-	-	-
BT	2	GMC	NT	NT	NT	B	F	F	SO	F	SO	-	42 ± 29	-	-	-	-	-	-	-
BT	3	GMC	NT	NT	NT	WH	F	F	SO	F	SO	-	-	-	10 ± 10	-	-	-	-	-
BT	4	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	73 ± 73	-	10 ± 10	10 ± 10	-	31 ± 31	-	-
WB	1	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	51 ± 20	-	-	-	-	-	-
WB	2	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	10 ± 10	-	82 ± 23	-	-	-	82 ± 17	-	-
WB	3	BMC	CU	NT	NT	WH	SO	D.W	F	WH	F	-	10 ± 10	-	-	-	-	-	-	-
TAM	1	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	10 ± 10	-	-	-	-	20 ± 12	-	-
TAM	2	GBMC	CU	NT	NT	F	SO	F	CA	T	F	20 ± 12	-	20 ± 12	-	-	-	-	-	-
TAM	3	GBMC	NT	NT	NT	F	SO	F	SO	F	SF	-	-	10 ± 10	51 ± 30	-	-	-	-	-
BUN	1	BMC	CU	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-
BUN	2	BMC	CU	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-
BUN	3	BMC	NT	NT	NT	F	SO	WH	SO	F	SO	-	-	-	-	-	-	-	-	-
BUN	4	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-

BT = Betoota, WB = Wheel Barrow Back, TAM = Tamarang, BUN = Bundella, PR = Property, P = Paddock, NT = No-Tillage, CU = Cultivated, W = Winter crop, S = Summer crop, WH = Wheat, SO = Sorghum, F = Fallow, CO = Cowpea, L = Lucerne, L&P = Lucerne and *Phalaris*, D.W. = Durum Wheat, B = Barley, CA = Canola, SF = Sunflower, T = *Triticale*, CG = Cattle grazing, - = No weeds, GMC = Grey medium clay, BSL = Brown sandy loam, GBMC = Grey brown medium clay, BMC = Brown medium clay

Seed banks with soil depth

The distribution of weed seeds at different sites was highly influenced by change in depth. As in the surface soil study, there were large variations between sites and between different depths within sites in the number of seedlings that emerged for different weed species. There were 15 weed species recorded in total but three of these (*V. arvensis*, *Rumex* spp. and *C. arvensis*) had negligible counts and hence were discarded. Over the 3 years the emerging weed species were similar. The 12 remaining species were *L. rigidum*, *P. aviculare*, *L. amplexicaule*, *Poa* spp., other grass spp., *C. colorata*, *F. parviflora*, *C. leptophyllum*, *S. oleraceus*, *G. pennsylvanica*, *A. arvensis* and *M. indica*.

Lolium rigidum, *P. aviculare* and *L. amplexicaule*

Lolium rigidum, *P. aviculare* and *L. amplexicaule* responded variedly in terms of their distribution at different sites and depths (Table 4.4). There was low *L. rigidum* emergence during 2004 at 0-2 and 10-15 cm depth and nil at other depths at BT. In general emergence decreased with increasing depth during the latter 2 years and the number of seeds at all the depths declined over the last 2 years at BT. In 2005, there were large numbers of *L. rigidum* in the surface which dropped sharply by 2006. *Polygonum aviculare* had nil emergence at all the depths except at 10-15 cm in 2004 at BT; the numbers in 2005 did not change greatly with increasing depth. In 2006, the seed numbers of *P. aviculare* were greatly concentrated in top 0-5 cm of soil (33 m⁻²) and lower at greater depth. In 2004, *L. amplexicaule* numbers at all depths were similar with none at 0-2 cm. The numbers decreased in 2005 sampling with no differences between depths. The surface seeds (0-5 cm) in 2006 were depleted with few numbers at greater depth.

The number of *L. rigidum* plants declined over the last 2 years of sampling and also declined with increasing depth of sampling at WB in 2004, however they remained statistically similar in 2005. Year 2004 was associated with few numbers at two of the four depths; in 2005 the numbers increased than decreased to zero in 2006. There were nil numbers at 0-2 cm and low numbers of *P. aviculare* emergence at other depths in 2004 at WB. The numbers increased in the following year except at 5-10 cm and then increased in 2006 except at surface. The numbers of *P. aviculare* declined with increasing depth in all the years. *Lamium amplexicaule* followed a similar trend.

There were no emergences in 2004 except at 0-2 cm. However, numbers increased in 2005 at all depths but decreased greatly in 2006 (Table 4.4).

The density of *L. rigidum* plants decreased with increasing depth in 2004 and it increased in 2005 at TAM. There were greater emergences at 5-10 cm depth in 2005 which decreased to nil in 2006. The number of *P. aviculare* plants increased with depth of sampling in 2004 down to 10 cm (Table 4.4). There were no clear depth distribution in 2005 and 2006 and the numbers decreased in the last 2 years of sampling at TAM. *Lamium amplexicaule* numbers also increased with depth in 2004 and 2006. Whereas, in 2005, the numbers declined with increase in depth distribution from top 0-5 cm to 10-15 cm depth. Generally, the numbers of *L. amplexicaule* declined in the last 2 years of sampling at TAM.

There was no emergence of *L. rigidum* or *P. aviculare* at any of the depths at BUN in any of the three years except for *L. rigidum* in 2004 at 0-2 cm depth and few in 2005 at three of the four depths. There were few *L. amplexicaule* emergences in 2004 with no clear depth distribution. The numbers were similar between depths in 2005 and 2006 except lower numbers at 10-15 cm depth in 2005 compared with other depth (Table 4.4). *Lamium amplexicaule* numbers decreased in last 2 years of sampling.

Crassula colorata and Poa and other grass spp.

In general, during the 3 years of sampling there were small scattered emergences of *Poa* and other grass spp. and *C. colorata* at all the four sites from different depths. In 2004, BT and WB showed few numbers of *Poa* spp. up to 5-10 cm depth (Table 4.5). The greatest numbers were located in top 0-5 cm (30 m⁻²) with the greater part at 2-5 cm depth (27 m⁻²) followed by at 5-10 cm depth numbers, with the least at 0-2 cm (3 m⁻²) and zero at 10-15 cm of sampling. Following the various management practices, there were nil emergences in the following 2 years. TAM and BUN had zero emergences of *Poa* spp. during all the 3 years and all 4 depths except at 0-2 cm at BUN with minimal emergence levels. Unidentified grass spp. were prevalent at the 5-10 cm depth at BT in 2005 and 2006. There was no emergence of other grass spp. at any of the other site except at WB in 2005 with little emergence from 2-15 cm depth. Zero or no *C. colorata* was found at 3 sites during the 3 years of sampling. At WB however, there were large numbers of *C. colorata* in 2004 with the greatest numbers

in top 0-5 cm soil and most of them concentrated at 2-5 cm depth (150 m⁻²). In 2005, the distribution pattern was similar to 2004 but the number of plants increased considerably. The numbers however, declined in 2006 with greatest plant numbers observed in top 0-5 cm soil and maximum numbers from 0-2 cm depth (77 m⁻²). During all the 3 years of sampling, the number of *C. colorata* plants decreased with increase in depth distribution.

Sonchus oleraceus, *M. indica* and *G. pensylvanica*

In 2004, there were zero or few emergences of *S. oleraceus* at BT, WB and BUN whereas at TAM the greatest numbers were contained in the top 0-5 cm of soil, with few at 0-2 cm and higher numbers at 2-5 cm. The numbers remained similar in first 2 years but declined in 2006 specifically in top 0-5 cm soil profile (Table 4.6). The numbers declined with increase of depth in all the 3 years. Similarly, at BT in 2005, the distribution of higher numbers of *S. oleraceus* seeds declined with increase in depth and the numbers decreased considerably in 2006. Betoota was the only site with few numbers of *M. indica* in 2004 and 2005 at 5-10 and 10-15 cm and at 5-10 cm depth in 2006. There were no emergences at all other sites and depths during the 3 years of sampling. At BT, the greatest emergence of *G. pensylvanica* was observed in 2004 in top 0-5 cm soil with nil numbers at 0-2 cm depth followed by lower numbers at 10-15 cm depth. Wheel Barrow Back and BUN had low emergence at individual depths and zero in others. There was no emergence in the following 2 years at all the 4 depths and the remaining sites.

Fumaria parviflora, *C. leptophyllum* and *A. arvensis*

At WB, TAM and BUN there was no emergence of *F. parviflora*, *C. leptophyllum* and *A. arvensis* during 2005 or 2006 (Table 4.7). Where emergence occurred in 2004 in TAM and WB it tended to occur from depth. No seedlings emerged from 0-2 cm. This was also true for *C. leptophyllum* and *A. arvensis*. At BT, there was a little emergence of *F. parviflora* in the top 5 cm of soil in 2004 followed by no emergence at the remaining depths. In 2005 the largest emergence of *F. parviflora* at BT was at 5-10 cm depth.

Table 4.4 Numbers of seedlings (m⁻²) emerging from seedbanks for individual weeds in 2004, 2005 and 2006 at different sites and depths on the Liverpool Plains in northern NSW.

PR	Depth (cm)	Soil	Tillage			2003 crops		2004 crops		2005 crops		<i>L. rigidum</i>			<i>P. aviculare</i>			<i>L. amplexicaule</i>		
			04	05	06	W	S	W	S	W	S	04	05	06	04	05	06	04	05	06
BT	0-2	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	2 ± 2	943 ± 195	34 ± 17	-	21 ± 15	16 ± 16	-	10 ± 6	-
BT	2-5	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	223 ± 58	5 ± 3	-	12 ± 6	17 ± 15	22 ± 4	10 ± 5	-
BT	5-10	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	134 ± 30	24 ± 15	-	54 ± 41	8 ± 3	25 ± 2	18 ± 2.5	2 ± 2
BT	10-15	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	2 ± 2	199 ± 64	9 ± 5	6 ± 4	19 ± 7	11 ± 7	23 ± 7	18 ± 6	6 ± 3
WB	0-2	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	14 ± 9	20 ± 8	-	-	65 ± 44	47 ± 3	2 ± 2	301 ± 150	64 ± 18
WB	2-5	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	27 ± 22	-	6 ± 4	15 ± 6	45 ± 10	-	170 ± 95	36 ± 14
WB	5-10	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	-	6 ± 4	-	33 ± 8	-	42 ± 24	22 ± 7
WB	10-15	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	9 ± 9	-	-	2 ± 2	2 ± 2	14 ± 6	-	10 ± 7	13 ± 11
TAM	0-2	GBMC	CU	NT	NT	F	SO	F	CA	T	F	6 ± 4	-	2 ± 2	3 ± 3	2 ± 2	-	8 ± 4	19 ± 12	2 ± 2
TAM	2-5	GBMC	CU	NT	NT	F	SO	F	CA	T	F	6 ± 3	12 ± 10	-	5 ± 5	14 ± 11	2 ± 2	12 ± 4	33 ± 9	5 ± 5
TAM	5-10	GBMC	CU	NT	NT	F	SO	F	CA	T	F	2 ± 2	32 ± 21	-	23 ± 19	8 ± 8	9 ± 9	41 ± 7	34 ± 11	14 ± 3
TAM	10-15	GBMC	CU	NT	NT	F	SO	F	CA	T	F	2 ± 2	12 ± 7	-	-	15 ± 13	2 ± 2	-	26 ± 8	10 ± 3
BUN	0-2	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	52	-	-	-	2 ± 2	-	2 ± 2	9 ± 6	3 ± 3
BUN	2-5	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	2 ± 2	-	2 ± 2	69 ± 65	-
BUN	5-10	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	2 ± 2	-	9 ± 5	79 ± 72	2 ± 2
BUN	10-15	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	6 ± 2	41 ± 41	3 ± 3

BT = Betoota, WB = Wheel Barrow Back, TAM = Tamarang, BUN = Bundella, PR= Property, NT = No-Tillage, CU = Cultivated, W = Winter crop, S = Summer crop, WH = Wheat, SO = Sorghum, F = Fallow, CO = Cowpea, L = Lucerne, L&P = Lucerne and *Phalaris*, T = *Triticale*, CG = Cattle grazing, CA = Canola, - = No weeds. GMC= Grey medium clay, BSL = Brown sandy loam, GBMC= Grey brown medium clay, BMC=Brown medium clay, * = same as above.

Table 4.5 Numbers of seedlings (m⁻²) emerging from seedbanks for individual weeds in 2004, 2005 and 2006 at different sites and depths on the Liverpool Plains in northern NSW.

PR	Depth (cm)	Soil	Tillage			2003 crops		2004 crops		2005 crops		<i>Poa</i> spp.			Other grass spp.			<i>C. colorata</i>			
			04	05	06	W	S	W	S	W	S	04	05	06	04	05	06	04	05	06	
BT	0-2	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	3 ± 3	-	-	-	-	-	-	-	3 ± 3	-
BT	2-5	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	27 ± 12	-	-	-	4 ± 4	-	-	-	-	-
BT	5-10	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	8 ± 8	-	-	5 ± 5	10 ± 10	-	-	-	-	-
BT	10-15	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	-	-	-	-	-	-	-	-	-
WB	0-2	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	9 ± 2	-	-	-	-	-	51 ± 43	986 ± 377	77 ± 33	
WB	2-5	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	11 ± 7	-	-	-	19 ± 19	-	150 ± 70	1191 ± 344	14 ± 7	
WB	5-10	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	6 ± 2	-	-	-	10 ± 10	-	40 ± 15	304 ± 214	3 ± 3	
WB	10-15	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	-	-	4 ± 4	-	7 ± 2	42 ± 20	-	
TAM	0-2	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	-	-	-	-	-	-	-	-	
TAM	2-5	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	-	-	-	-	-	-	-	-	
TAM	5-10	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	-	-	-	-	-	-	-	-	
TAM	10-15	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	-	-	-	-	-	-	-	-	
BUN	0-2	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	2 ± 2	-	-	-	-	-	-	-	-	
BUN	2-5	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-	
BUN	5-10	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	3 ± 3	
BUN	10-15	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-	

BT = Betoota, WB = Wheel Barrow Back, TAM = Tamarang, BUN = Bundella, PR= Property, NT = No-Tillage, CU = Cultivated, W = Winter crop, S = Summer crop, WH = Wheat, SO = Sorghum, F = Fallow, CO = Cowpea, L = Lucerne, L&P = Lucerne and *Phalaris*, T = *Triticale*, CG = Cattle grazing, CA = Canola, - = No weeds. GMC= Grey medium clay, BSL = Brown sandy loam, GBMC= Grey brown medium clay, BMC=Brown medium clay, * = same as above.

Table 4.6 Numbers of seedlings (m⁻²) emerging from seedbanks for individual weeds in 2004, 2005 and 2006 at different sites and depths on the Liverpool Plains in northern NSW.

PR	Depth (cm)	Soil	Tillage			2003 crops		2004 crops		2005 crops		<i>S. oleraceus</i>			<i>M. indica</i>			<i>G. pensylvanica</i>			
			04	05	06	W	S	W	S	W	S	04	05	06	04	05	06	04	05	06	
BT	0-2	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	133 ± 18	-	-	-	-	-	-	-	
BT	2-5	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	78 ± 20	5 ± 3	-	-	-	20 ± 6	-	-	
BT	5-10	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	42	32	6 ± 6	3 ± 3	3 ± 3	2 ± 2	4 ± 3	-	-
BT	10-15	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	2 ± 2	28 ± 26	2 ± 2	20 ± 10	3 ± 3	-	12 ± 7	-	-	
WB	0-2	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	4 ± 4	-	-	-	-	-	-	-	
WB	2-5	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	6 ± 4	-	-	-	-	2 ± 2	-	-	
WB	5-10	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	5 ± 3	-	-	-	3 ± 3	-	-	
WB	10-15	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	-	-	-	-	-	-	-	
TAM	0-2	GBMC	CU	NT	NT	F	SO	F	CA	T	F	3 ± 2	10 ± 4	-	-	-	-	-	-	-	
TAM	2-5	GBMC	CU	NT	NT	F	SO	F	CA	T	F	10 ± 2	9 ± 2	-	-	-	-	-	-	-	
TAM	5-10	GBMC	CU	NT	NT	F	SO	F	CA	T	F	12 ± 7	4 ± 2	9 ± 4	-	-	-	-	-	-	
TAM	10-15	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	2 ± 2	2 ± 2	-	-	-	-	-	-	
BUN	0-2	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	3 ± 3	2 ± 2	-	-	-	-	-	-	
BUN	2-5	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-	
BUN	5-10	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	3 ± 2	-	-	
BUN	10-15	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	2 ± 2	2 ± 2	-	-	-	-	-	-	

BT = Betoota, WB = Wheel Barrow Back, TAM = Tamarang, BUN = Bundella, PR= Property, NT = No-Tillage, CU = Cultivated, W = Winter crop, S = Summer crop, WH = Wheat, SO = Sorghum, F = Fallow, CO = Cowpea, L = Lucerne, L&P = Lucerne and *Phalaris*, T = *Triticale*, CG = Cattle grazing, CA = Canola, - = No weeds. GMC= Grey medium clay, BSL = Brown sandy loam, GBMC= Grey brown medium clay, BMC=Brown medium clay, * = same as above.

Table 4.7 Numbers of seedlings (m⁻²) emerging from seedbanks for individual weeds in 2004, 2005 and 2006 at different sites and depths on the Liverpool Plains in northern NSW.

PR	Depth (cm)	Soil	Tillage			2003 crops		2004 crops		2005 crops		<i>F. parviflora</i>			<i>C. leptophyllum</i>			<i>A. arvensis</i>		
			04	05	06	W	S	W	S	W	S	04	05	06	04	05	06	04	05	06
BT	0-2	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	2 ± 2	65 ± 59	-	-	-	-	-	-	-
BT	2-5	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	2 ± 2	51 ± 26	-	9 ± 4	-	-	-	10 ± 6	-
BT	5-10	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	178 ± 33	-	29 ± 17	-	-	11 ± 7	12 ± 4	-
BT	10-15	GMC	NT	NT	NT	L&P	F	L&P	F	L&P	L&P	-	96 ± 44	2 ± 2	15 ± 7	-	-	2 ± 2	3 ± 3	-
WB	0-2	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	-	-	-	-	-	-	-
WB	2-5	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	-	-	-	-	15 ± 9	-	-
WB	5-10	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	-	-	-	-	-	-	31 ± 15	-	-
WB	10-15	BSL	NT	NT	NT	WH	L	CO	SO	CG	F	31	-	-	-	-	-	-	-	-
TAM	0-2	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	-	-	-	-	-	-	-	-
TAM	2-5	GBMC	CU	NT	NT	F	SO	F	CA	T	F	-	-	-	11 ± 4	-	-	-	-	-
TAM	5-10	GBMC	CU	NT	NT	F	SO	F	CA	T	F	4 ± 3	-	-	47 ± 45	-	-	-	-	-
TAM	10-15	GBMC	CU	NT	NT	F	SO	F	CA	T	F	6 ± 2	-	-	-	-	-	-	-	-
BUN	0-2	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-
BUN	2-5	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-
BUN	5-10	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-
BUN	10-15	BMC	NT	NT	NT	WH	SO	F	SO	F	SO	-	-	-	-	-	-	-	-	-

BT = Betoota, WB = Wheel Barrow Back, TAM = Tamarang, BUN = Bundella, PR= Property, NT = No-Tillage, CU = Cultivated, W = Winter crop, S = Summer crop, WH = Wheat, SO = Sorghum, F = Fallow, CO = Cowpea, L = Lucerne, L&P = Lucerne and *Phalaris*, T = *Triticale*, CG = Cattle grazing, CA = Canola, - = No weeds. GMC= Grey medium clay, BSL = Brown sandy loam, GBMC= Grey brown medium clay, BMC=Brown medium clay, * = same as above

4.4. Discussion

Seedbank species and numbers

The prominent weed species found across these four properties were *L. rigidum*, *L. amplexicaule*, *Poa* spp., *C. colorata*, *P. aviculare*, *S. oleraceus*, *F. parviflora*, *C. leptophyllum* and *A. arvensis*. Walker *et al.* (2004) similarly found *L. rigidum* and *P. aviculare* as the common weeds specific to southern Queensland and northern New South Wales among other weeds. Generally, relatively low seedbanks (< 62 m⁻²) of *L. rigidum* were found in most areas where glyphosate resistance had been detected, possibly because of low dormancy of *L. rigidum*. The exception was at the two sites; BT2 (1507 m⁻²) and BUN2 (502 m⁻²) which had high levels. The numbers on all properties ranged from (10-1507 m⁻²). Both these sites had cereal crop histories which would promote *L. rigidum* seed build-up if it was not well controlled. By 2006, only low levels of seedbanks of *L. rigidum* remained probably because, with the occurrence of resistant populations, cropping and weed management practices had been targeted by the farmers over the last few years to deplete the *L. rigidum* seedbank. Still, the large numbers of *L. rigidum* and other weeds such as *L. amplexicaule* (10-502 m⁻²), *P. aviculare* (10-132 m⁻²), *S. oleraceus* (10-82 m⁻²) and *C. colorata* (255-1099 m⁻²) that appeared in 2006 increase the vulnerability of these species to acquiring resistance to one or more herbicides. Walker *et al.* (2002, 2004) found *S. oleraceus* and *L. rigidum* among other weeds to have a possible threat of acquiring resistance to one or other group of herbicides.

Spraying of non selective herbicides such as glyphosate to kill other non herbicide resistant weeds followed by Spray.Seed (paraquat + diquat) during the fallow season and before sowing of the crop, and spraying of other grass and broad leaf selective herbicides such as MCPA, tralkoxydim, trifluralin, metsulfuron, metolachlor and fluroxypyr in association with fallow-sorghum rotations, are probably helping to deplete the seedbanks. The grain grower at BT sprayed glyphosate on 8 occasions during the winter fallow and before sowing the new crop. The grower was unaware of the fact that the repeated use of herbicide would increase the level of herbicide resistance. From the farmers' perspective glyphosate was highly effective in controlling mixed weed flora which would otherwise need to be controlled by use of a range of individual herbicides for individual weeds. Farmers need to select better

management strategies while monitoring the populations of weeds reappearing. Alternative herbicides or other practices including straw burning may be needed under conditions of resistance development.

Variation between properties and paddocks

There were large variations of seedbank species and numbers between the properties and the paddocks for surface and depth studies. Webster *et al.* (2003) reported differences in seedbanks between the field sites with the same crop rotation. Among properties, BT and BUN had greatest *L. rigidum* numbers. *Polygonum aviculare* and *L. amplexicaule* were highest at TAM and WB, whereas *Poa* spp., other grass spp., *C. colorata*, *S. oleraceus* and *G. pensylvanica* had the largest seedbanks at WB. All these species may build up to serious levels in the future. The variability in numbers at each property may be due to previous infestation history of that particular weed and to management practices followed in previous years. Moss and Cussans (1982) found that *A. myosuroides* has been encouraged by the increase in the growing of winter cereals, earlier sowing and adoption of minimum tillage techniques.

WB sites had low *L. rigidum* levels but WB1 and WB2 had high *Poa* spp. and *C. colorata* levels during 2004 possibly because the short term legume crops could not provide sufficient competition to suppress these less competitive weeds. There were nil numbers of *Poa* spp. and *C. colorata* observed at WB 3 possibly due to differences in soils types and change in management factors including crop rotations. Similarly, Chikoye and Ekeleme (2001) found differences in seed density and species diversity of the seed bank in the Netherlands due to change in soil type and climatic conditions.

Overall, *Poa* spp. and other grass spp., *C. colorata*, *M. indica* and *G. pensylvanica* had zero or low seedbank levels at most of the properties and therefore they are unlikely to interfere with crop growth in the future. There are variable *S. oleraceus* numbers on some properties; at WB and TAM considerations need to be given to prioritise the control of this weed in the future. However, *C. colorata* at WB persisted initially with large numbers and may need more targeted management in future.

In 2006, *P. aviculare* seedbanks were nil in most of paddocks except for three where necessary management is required to keep them at lower levels. At WB and TAM, *L.*

amplexicaule numbers are at high levels and farmers need adopt a strategic approach to reduce these seedbanks. Large numbers of *P. aviculare* at WB and lesser numbers at BT and TAM are still sufficient to cause crop competition in the near future and so require effective control. *L. amplexicaule* had greater populations at WB with lower levels at the other 3 sites; this will require management changes to keep the numbers low in future cropping cycles.

Variation between years

Surface studies showed that seedbanks of some species varied greatly between years. Large difference in the variation of seedbanks over the years in surface studies may be due to variability and patchiness of seedbanks even at shorter distances. In our study each year GPS was used to re-site and the transects were located within 0.5 m accuracy. Such patchiness may have contributed to variation between years but this cannot account for all the variations given the number of replicate transects and number of soil cores along each transect.

Across all the sites, *Poa* spp., other grasses, *G. pensylvanica*, *M. indica* and *C. colorata* were more prominent in 2004 rather than in 2005 and 2006; this was not expected due to late sampling in 2004. This would suggest that these species were possibly seasonally dominant species i.e. vary with year. On the other hand the presence of *L. rigidum*, *L. amplexicaule*, *S. oleraceus* and *P. aviculare* varied between years depending on the paddock, suggesting that their occurrence was more determined by farm management practices. Similar results for different weeds were reported by Felix and Owen (2001).

The TAM site had the tillage history of both cultivation and no tillage and lower *L. rigidum* levels were reported in 2005 and nil in 2006, possibly suggesting that active measures were being taken by the grower to control *L. rigidum*. However, a high population of *L. amplexicaule* in surface studies was common on all the three paddocks in 2006 suggesting that there may be a weed population shift occurring under present weed control systems or that this property has had a history of *L. amplexicaule* infestation. The extremely high figures of *L. amplexicaule* in 2005 at TAM 3 suggest that the TAM 3 management system of continuous no-tillage and

winter fallows could be inducing a potential problem, assuming the weed seedbank levels are viable under field conditions.

Mayor and Dessaint (1998) reported an increase in the seed banks of *Capsella bursa-pastoris* due to the advantage of poorly competitive crops and in the absence of herbicide pressure. At BUN, there were large populations of *L. rigidum*, *P. aviculare* and *L. amplexicaule* in 2005 probably because the wheat-sorghum rotation was followed from many years under a no-tillage system. The weed numbers decreased drastically in 2006 probably because of changes made in crop rotation and management practice. Sosnoskie *et al.* (2006) observed that crop sequence and tillage system influenced weed species density and diversity and therefore community structure.

The depth studies conducted over the three years showed differences in seedbank numbers of weeds over years. The BT sampling site had large numbers of *L. rigidum* plants in 2005 which decreased greatly with ongoing management practices in 2006. Granados and Torres (1993) suggested that seedbank level was affected by the previous infestation severity and also by other environmental factors such as rainfall, wind and tillage practices which led to dispersion of seed.

At BT, the numbers declined in later years possibly due to the lucerne and *Phalaris* (L&P)-fallow (F) rotation in 2004 and L&P-L&P in 2005 as it created a shade and smothering effect, not allowing the *L. rigidum* seeds to emerge. The practice produced a similar influence on *L. amplexicaule* but *P. aviculare* numbers increased over the years with similar rotations. WB and TAM paddocks had little or no *L. rigidum* plants in 2005 and 2006 in these depth studies may be due to patchiness which contributed to variation between years as discussed above.

Depth studies at WB indicate that the crop rotation in 2004 increased the numbers of *P. aviculare* in 2005 and the 2005 rotation of cattle grazing-fallow did not decrease the plant numbers in 2006 possibly because cattle grazing had little effect on the survival of *P. aviculare*. *Lamium amplexicaule* had variable plant emergences in all the 3 years at WB and all the properties despite similar rotations as for other weed species. The numbers increased in 2005 at all the depths but later decreased in 2006

with the usual tillage and crop rotations. Cultivations carried out at TAM in 2004 had a considerable negative effect on the numbers of *L. rigidum*, *P. aviculare* and *L. amplexicaule* emerging in 2005. In the present samplings, later in 2006, the seed numbers were restricted probably due to effective burying or killing of most of the seeds as a result of cultivation in 2004. BUN had zero emergences of *L. rigidum* and *P. aviculare* in both the years but had few numbers of *L. amplexicaule* in 2005 which decreased in 2006 due to the existing management practices.

There was little or nil emergence of *Poa* spp., grass spp. and *C. colorata* from seedbanks at TAM and BUN in all the 3 years of sampling. The number of *Poa* spp. decreased to zero in the final 2 years possibly as a result of L&P-fallow and L&P-L&P rotations at BT and cowpea-sorghum and cattle grazing-fallow at WB in 2005 and 2006 respectively. There were few grass spp. at BT and WB possibly because these are seasonally dominant species. *Sonchus oleraceus* and *Fumaria parviflora* were strongly represented in the BT site seedbank in 2005 depth studies but they decreased to nil or low levels in the following year possibly as a result of ongoing crop rotations and no-tillage in association with other current management practices. It is not possible to say that the effects were solely due to crop rotational changes or following no-till for previous years. However, Barberi *et al.*(1998) suggested that differences of weed numbers among systems depended mainly upon weed control efficacy rather than upon tillage effects.

Greater emergences of *C. leptophyllum* and *G. pensylvanica*, *A. arvensis* and *M. indica* were observed in 2004 followed by zero levels in the later 2 years, possibly as a result of the previous year crop rotations in conjunction with existing management practices. At WB, *S. oleraceus*, and *A. arvensis* had greater numbers in 2004. The plant numbers decreased to nil in later years of sampling possibly due to the introduction of short term legume cropping in association with cereal crop.

Variation with depth

Seed numbers and species varied between depths of sampling. Some weed species increased with an increase in depth while others decreased. The greatest *L. rigidum* numbers were at 0-2 cm. The numbers decreased substantially at 2-5 cm depth as a result of continuous no-till practice from the last 3-4 years.

In 2005, at the BT site the seeds of *L. rigidum* were in large numbers on the surface and at depth possibly from the fresh seed shed from the previous year and from others which were buried deep due to their dispersal by action of insects or rodents or they were apparently buried deep sometime in early years when crops were cultivated. Due to short viability of *L. rigidum*, the seeds did not survive in the later year in the deep soil profile. However, there were only low numbers in top layer of the soil in 2006 which presumably decreased in viable numbers due to legume and *Phalaris* rotations.

Seedbanks of *P. aviculare* were also high in the 0-5 cm depth and decreased with increasing soil depth possibly due to no-tillage farming over the years and little diffusion through the cracks in the soil to lower depths. Similar results were found by Pareja *et al.* (1985). Nevertheless, seeds were found to 15 cm depth which could have been buried during the sowing operation or have remained buried from previous cultivations.

There were small numbers of *Poa* spp. in 2004 with the greatest being at 2-5 cm depth at BT and WB under continuous no-till for many years. Similar results were reported by Barberi *et al.* (1998) under continuous maize cropping system. Wheel Barrow Back in 2004 was associated with higher numbers of *C. colorata* which were more concentrated at 2-5 cm depth possibly due to continuous use of no-till, which provided greater concentrations in top layers of soil. The short term legume crop followed by sorghum may have had a synergistic effect in reducing the numbers to dramatically lower levels under the present system of management. The incorporation of cattle grazing as a tool for managing weeds at WB provided possibilities for decreasing the seedbanks in 2006 by grazing the weeds and thereby decreasing the numbers of seed shed in the field.

Sonchus oleraceus numbers decreased with increasing sampling depth showing clear differences due to the use of no-till in previous years. However, *F. parviflora*, *C. leptophyllum*, *A. arvensis* and *M. indica* numbers were greater at 5-10 cm depth; the possible reason for this may be that the seeds had a chance to move through the soil profile due to the smaller seed size. Also presumably many of the small seeded species germinated in the field from 0-2 cm but not at the greater depths. When greater depths were brought into the polyhouse, it may have stimulated buried seeds

to germinate. Granados and Torres (1993) found that the soil seed density of *Orobanche crenata* increased from year to year and was higher in the surface layer (5-10 cm depth). A similar case occurred with *C. leptophyllum* at BT which was more concentrated at greater depth.

Depth studies suggest similar variations in weed numbers and species with depth of sampling across properties. *Lolium rigidum* populations generally decreased with increase in depth however there were some seeds at greater depth at BT. Crop rotations and other management practices at the BT site appeared ineffective in decreasing the numbers to adequately low levels.

4.5. Conclusions

- Low numbers of *L. rigidum* seed were found in the seedbank, most areas where glyphosate resistance had been detected. However, there were some exceptions such as at the two sites BT2 (1507 m⁻²) and BUN2 (502 m⁻²) which had high levels. The numbers across all properties ranged from 10-1507 m⁻².
- Previous studies suggest risk of herbicide resistance development for *P. aviculare* and *S. oleraceus*. The prevailing numbers of these (10-132 and 10-82 m⁻² respectively) and other weeds such as *C. colorata* and *L. amplexicaule* in the current study indicate that their changing levels will need to be continued to be monitored and appropriate management strategies adopted accordingly (chapter 7).
- The greatest *L. rigidum* numbers were in the top 0-5 cm of soil. Of these most of them were concentrated at 0-2 cm as a result of continuous no-till practice from last 3-4 years. The numbers of *S. oleraceus* and *P. aviculare* also decreased with increase in depth and most of their seedbanks lay in the top 0-5 cm of soil. It is important to know how depth affects the survival of these weeds (chapter 5).

- The seedbank species remained unchanged over the 3 years of sampling, at one time of the year however, there was variability in the numbers emerging each year. Generally, *L. rigidum* and *S. oleraceus* numbers declined under the prevailing management practices (tillage, crop rotations and herbicides). However, low numbers were still persistent which could lead to explosions in numbers and competition over coming years. *Polygonum aviculare* numbers in 2006 were still persisting compared with previous years and therefore need to be given due consideration in terms of management (chapter 7).

Chapter 5. Dormancy/Viability

5.1. Introduction

Dormancy is the internal condition of the seed that impedes germination under otherwise adequate hydric, thermal and gaseous conditions. However, once the seed is released from dormancy provided conditions are correct, germination proceeds in a wide range of environments that are commonly found in cropping fields (Benech Arnold *et al.* 2000). Buried weed seeds are of perpetual concern to agriculturalists (Omami *et al.* 1999). The persistence of a weed seedbank depends on the proportions of seed that either germinate or remain dormant (Buhler *et al.* 1998). Dormancy is frequently viewed as one of the main mechanisms by which weeds are able to invade and persist in agricultural fields (Ghersa 2005).

Germination, emergence, viability and dormancy of seeds are largely dependent on depth of seed burial. Benvenuti *et al.* (2001) found that *Rumex obtusifolius* seedlings did not emerge when seeds were buried > 8 cm deep, while others have found that seeds of several weed species buried below the soil surface were less dormant when compared with seeds on the soil surface (Franzenburg and Owen 2002, Taylorson 1969). Navie *et al.* (1998) found that the innate dormancy of *Parthenium hysterophorus* was lost after 2 months of burial in the field, although *in situ* germination of buried seed remained low for at least 24 months. Campbell and Nicol (1997) reported that the longer and deeper the burial of *Cassinia arcuata* seeds in the soil and the older the seeds, the fewer seeds that germinated when recovered. The main cause of loss during burial was germination in the soil and destruction by soil organisms. Seeds of four subshrubs germinated readily if placed on the surface or partially pressed into the soil. Emergence was reduced by covering seed with soil to a depth of less than 1 mm. Rate of emergence also decreased with increasing depth of placement (Mayeux 1983).

Zorner *et al.* (1984a) reported that persistence of *Kochia scoparia* increased with depth of burial. Seed loss from the initially dormant populations was limited to germination *in situ*, but seed loss from the initially non dormant population included significant viability loss at burial depths of 10 cm or less. Gleichsner and Appleby

(1989) found that both surface sown and buried *Bromus rigidus* seed were depleted within 15 months. Persistence of surface sown seed declined relatively slowly during the first year, falling from 83 to 62 to 23%, after 1, 9 and 12 months. Seed viability decreased with increased burial duration and most buried seeds lost viability within 1.5 years at seasonally flooded or permanently flooded sites, whereas seeds buried at non-flooded sites survived over a period of up to 2 to 2.3 years (Van *et al.* 2005).

Persistence, dormancy and viability are also influenced by environmental conditions. The annual weed seeds of arable land were relatively long-lived, but otherwise there appeared to be little relationship between seed persistence and habitat (Roberts 1986). Seed dormancy of *Beta vulgaris* varied with season: the proportion of non-dormant seeds increased during winter (appearance of secondary dormancy) and decreased during the remaining seasons (loss of dormancy) (Sester *et al.* 2006). In the laboratory, rates of dormancy induction in canola seeds were positively correlated with increasing temperature and water stress. An increase in the ungerminable portion of the seedbank was observed in the high-dormancy genotypes as soil temperatures increased during spring. Soil texture had little effect. Seeds buried in organic soils decreased viability significantly faster than those in sandy loam soils due to microbial action (Gulden *et al.* 2004).

Annual ryegrass (*Lolium rigidum*) is one of the most serious weed problems of annual cropping in Australia and provides the greatest number of herbicide resistant weed populations (Preston *et al.* 1999). The over-reliance on herbicides has resulted in the evolution of herbicide resistance in many *L. rigidum* populations (Gill 1995, Llewellyn and Powles 2001). *Lolium rigidum* is a prominent weed in the southern Mediterranean regions of Australia with its wet winters and dry summers. As a result, most of the research work related to *L. rigidum* has been done in this region. The incidence of glyphosate resistance in *L. rigidum* has continued to increase, with 54 confirmed glyphosate resistance populations to date occurring in Western Australia, South Australia, Victoria and New South Wales (Preston 2006). A farm survey of the lower Liverpool Plains in northern NSW in 2001, showed that glyphosate resistant *L. rigidum* was present on at least 10 properties, with infestations varying from small patches of plants to being widespread across the whole property (Storrie and Cook 2002).

The Liverpool Plains is a significant cropping area of the northern grains region and has wetter summers and drier winters. In order to successfully control the glyphosate resistant *L. rigidum*, it is important to deplete its seed bank. Such depletion requires a thorough knowledge and understanding of the key factors affecting the germination, emergence and dormancy of *L. rigidum* seeds. Time and depth of seed burial are particularly important and have been investigated for a wide range of weeds. However, little is known about the effects of other factors such as rainfall pattern and soil type on the longevity or survival of weeds particularly in the northern grain region of Australia. *Lolium rigidum* is thought to have a very short dormancy cycle (Peltzer and Matson 2002b) but the factors which directly or indirectly affect dormancy, viability, germination and emergence of *L. rigidum* require further research.

One experiment was initiated under controlled polyhouse conditions at the University of New England, Armidale and a second under field conditions at the Tamworth Agricultural Institute, Department of Primary Industries, Tamworth. The first experiment examined the effect of rainfall pattern (winter dominant versus summer dominant), soil type, depth of burial and duration of burial on the germination, emergence and dormancy of glyphosate resistant *L. rigidum* seeds while the second examined the effect of depth of burial and duration of burial on the germination and dormancy of glyphosate resistant *L. rigidum* seeds under northern NSW grain region field conditions and a single soil type of red brown light clay.

5.2. Methods

Armidale experiment

Site

The University of New England in Armidale is situated at 30° 30' S and 151° 40' E. Armidale has very unpredictable weather throughout the year with minimum temperature commonly reaching -9°C during frosty winters and the summer temperature typically restricted to a maximum of 35°C. The trial was conducted in a polyhouse equipped with a data logger (providing air and soil temperature data every hour), irrigation facilities and ventilation.

Treatments

The treatments were as follows:

- two rainfall patterns: one simulating the rainfall of Tamworth in northern New South Wales (summer dominant) and the other from Hamilton in Victoria (winter dominant);
- two soil types: one a clay and the other a sandy loam;
- two burial depths: 5 cm and 10 cm; and
- four times of exhumation, every 4 months.

The moisture condition treatments were selected to simulate patterns of rainfall at Tamworth in northern NSW (northern rainfall region) where the behaviour of *L. rigidum* seedbanks is largely unknown and Hamilton in southern Victoria (southern Mediterranean rainfall region) under conditions in which *L. rigidum* behaviour has previously been studied. Although the average annual rainfall is the same at both locations (approximately 674 mm), the distribution of rainfall patterns is opposite. Hamilton receives most of its rainfall in winter, whereas Tamworth is wet mostly in summer (Figure 5.1). Two contrasting soil types were also tested. The first was from the Laureldale Research Station, in Armidale, and was medium heavy clay chocolate basalt (0-10 cm depth, pH 6.4, organic matter 2.8%) with good water holding capacity (denoted as Laureldale) and the second from the Kirby Research Station which was a greyish brown fine sandy loam (0-10 cm depth, pH 6.2, organic matter 1.8%), with poor water holding capacity (denoted as Kirby).

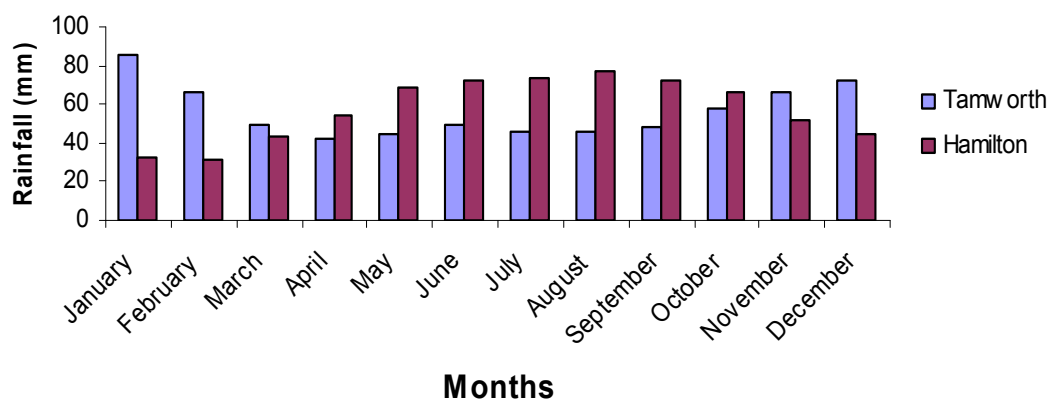


Figure 5.1 Total monthly rainfall (mm) for Hamilton and Tamworth (average of 10 years)

Design

Each treatment was replicated four times in a factorial (soil x moisture x depth x exhumation time) randomised complete block design experiment (Figure 5.2).



Figure 5.2 Experiment setup in polyhouse at Armidale.

Initial viability test

A germination test was conducted to determine the initial viability and dormancy of seeds immediately before the commencement of the experiment. Four replicates of 50 seeds were placed in Petri dishes lined with Whatman No.1 filter paper. The petridishes were placed in a growth cabinet at 25/15°C day and night temperatures, and 12 hr day (light)/ 12 hr night (dark). Deionised water was applied to the plates when required. After 15 days, all the germinated seeds were counted and discarded and the non germinated seeds were soaked in water overnight and then dissected length wise and diagonally across the embryo and later soaked in a 10% solution of 2,3,5-triphenyl tetrazolium chloride overnight in the dark. Non viable seed was not coloured whereas viable (dormant) seed produced a pink stain on the exposed dissected embryo (Hartmann *et al.* 1981).

Burial of seed

Nylon sheets of 0.5 mm mesh were used to make bags for burial of the seeds. The 10 x 12 cm bags were folded and stitched along three sides with nylon thread and the inlet of the bag was folded on top to prevent any soil or seed loss. The size of bags were 10 x 12 cm. The confirmed glyphosate resistant *L. rigidum* seeds (chapter 4) were harvested during December, 2004 from the Liverpool Plains of northern NSW and stored at 4°C for 3 months. Fifty seeds weighing in total approximately 0.125g were placed in each nylon bag mixed with 200 cm³ of soil. The soil used to fill the

bags were either of the two experimental soil types which were previously incubated for 4 hours at 80°C to kill other viable weed seeds. Plastic pots with a diameter of 19 cm and 24 cm high with holes at the bottom were lined with paper towel, filled with the appropriate soil and placed on shallow plastic trays on a gravel base on the ground. The bags containing *L. rigidum* seeds were placed at either 5 cm or 10 cm depth. The trial commenced on 9 March, 2005 and continued until 9 July 2006. The polyhouse was heated from May to August as the outside temperatures fell below 0°C overnight during these months. The temperature in the polyhouse was recorded over the period of experiment and presented in Figure 5.3.

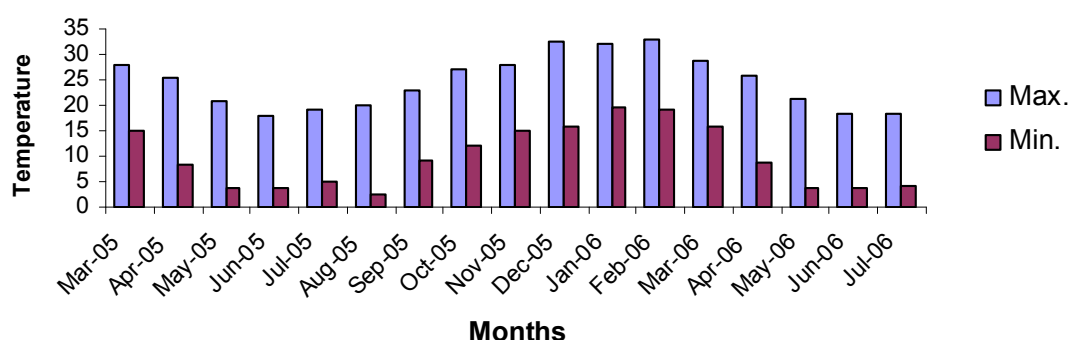


Figure 5.3 Mean monthly temperature (°C) (Max and Min) for 2004 and 2005 in the polyhouse at Armidale.

Simulation of rainfall

The average monthly rainfalls for Tamworth and Hamilton for the last 10 years were collected online from the website of the Bureau of Meteorology, Australia. The rainfall for each month was equally divided into four parts to calculate watering of the pots on a weekly basis. A small plastic bottle cut at the top with holes in the base was used to simulate the actual rainfall. The quantity of water applied to each pot was calculated as follows:

$$\text{Rainfall (cm}^3\text{)} = \pi r^2 \times \text{rainfall per week cm};$$

where r = radius of the pot to be watered.

Initially, the simulated rainfall was added to the pots every week. But the cool temperatures during May and June in the polyhouse between 0°C and 9°C, kept the pots too wet. It was therefore decided to water the pots once every fortnight i.e. twice a month. Therefore, the rainfall for each month was divided into two parts and the amount of water to be added fortnightly was calculated accordingly (Table 5.1).

Table 5.1 Fortnightly application of water per pot (ml) over the 16 month trial period at Armidale for Tamworth and Hamilton simulations.

Month	Fortnightly rainfall (ml)	
	TAMWORTH	HAMILTON
March, 2005	700	600
April, 2005	600	800
May, 2005	600	950
June, 2005	700	1000
July, 2005	650	1050
August, 2005	650	1100
September, 2005	700	1000
October, 2005	800	900
November, 2005	950	900
December, 2005	1000	650
January, 2006	1200	450
February, 2006	950	450
March, 2006	700	600
April, 2006	600	800
May, 2006	600	950
June, 2006	700	1000
July, 2006	650	1050

Seed exhumation

Seed bags were exhumed every 4 months (Table 5.2). Thirty two bags were exhumed, one from each of thirty two pots on each occasion, and kept in the polyhouse to dry the soil while the remaining pots in the trial were re-randomised at each exhumation. The soil from each bag was passed through three sieves of different gauges (placed on top of each other with the coarsest one on the top and the finest at the bottom) to remove any soil clods and plant material and to separate out the non germinated *L. rigidum* seeds. The nongerminated *L. rigidum* seeds were identified and counted using a magnifying lens and forceps. The separated seeds were then germinated and tested for dormancy using tetrazolium chloride, as per the initial viability test described earlier (page 6).

Table 5.2 Exhumation of bags schedule over 16 months period.

Activity	Date
Start of experiment	9 March, 2005
1 st Exhumation	9 July, 2005
2 nd Exhumation	9 November, 2005
3 rd Exhumation	9 March, 2005
4 th Exhumation	9 July, 2006
Termination date	9 July, 2006

There were five data sets obtained in this trial. They were:

- a. viable seeds (germinable + dormant seeds);
- b. germinable viable seeds;
- c. dormant viable seeds;
- d. dead seeds (germinated in pots) = total seeds in bag (50) – (number of viable seeds + number of emerged seeds); and
- e. emerged seedlings from pots.

Seedling pot emergence

During the 16 months of the experiment, the *L. rigidum* seedlings which emerged were counted and uprooted as and when they emerged in the pots (Figure 5.4). The data for emergence is presented as ‘emergence over time’ and the sum of these emerged seedlings at the termination of the experiment is presented as the total emergence. The other emerged weed species in the pots were hand pulled from time to time.

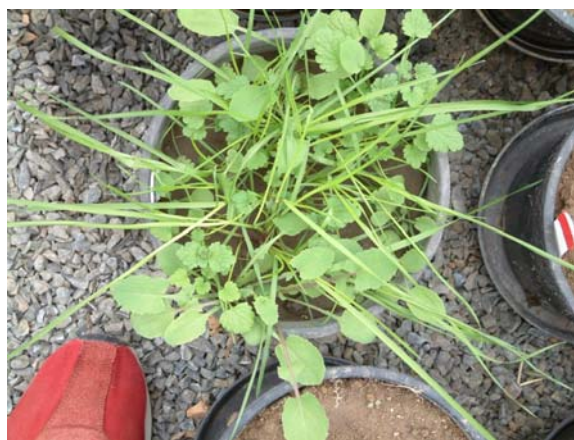


Figure 5.4 *Lolium rigidum* emergence from the buried seeds in nylon bags.

Data analysis

The non-linear least squares regression function in S-Plus 2000[®] was used to fit data to several response variables (MathSoft. 1999). The data for viable seeds, germinable viable and dormant viable seeds over time were fitted with an inverted Michaelis-Menten function:

$$Y= 100-((100-a) * x/ (b + x)) \quad \text{(Equation 5.1)}$$

where a = lower asymptote, b = level of curvature (rate of reduction of the parameter) and x = time of exhumation of bags.

Data for the dead seeds were fitted with the Michaelis-Menten function

$$Y= a * x / (b + x) \quad \text{(Equation 5.2)}$$

where a = upper asymptote, b = level of curvature (rate of increase of the parameter), x = time of exhumation of bags.

The non-linear regressions are presented with 95% confidence limits.

Treatment effects were evaluated at individual time points for individual pot emergence over time and total emergence using the ANOVA function. Diagnostic plots were used to check the homogeneity of variance and normality of the data for each response variable and no transformations were necessary. Generalised linear models (GLM) with a Poisson distribution were used to determine the effects of the treatments at individual points for viable seeds, germinable viable seeds, dormant viable seeds and dead seeds. The GLM output contained an Analysis of Deviance table with a Chi-square test for significance of the explanatory variables. Goodness of fit was confirmed by comparing the residual deviance with the underlying Chi-square distribution. The P values for ANOVA and GLM are presented in the results section to indicate the level of significance. Data for the emergence of *L. rigidum* seeds over time varied irregularly and were, therefore, compared using means and standard errors.

Tamworth experiment

Site

The Tamworth Agricultural Institute (TAI) at Calala is situated approximately 100 km south of Armidale in the New England region of New South Wales, about 10 km south east of the city of Tamworth at 31° 08' S and 150° 59' E at an elevation of 450 m above sea level. Tamworth is located on the edge of the Liverpool Plains, and at the

eastern edge of the northern grain region of NSW. A seed burial experiment was conducted in one of the long-term cropping fields at the Institute (Figure 5.5). The soil of the experimental field was dark reddish brown dry light clay (0-10 cm, pH 6.5, organic matter 3.0%). Calala receives an annual rainfall of 675 mm with almost 65% falling in the 6 months, October to March. A relatively flat corner area of the field was selected and kept free from weeds.

Treatments

The treatments were as follows:

- three burial depths: surface, 5 cm and 10 cm; and
- seven times of exhumation: seed bags were exhumed at 2, 4, 6, 9, 12, 15 and 18 months after initiation of the experiment.

Design

Each treatment was replicated four times in a factorial (depth x exhumation time) randomised complete block design experiment.



Figure 5.5 Seed burial experiment established at the Tamworth Agricultural Institute.

Burial of seed

Preparation and filling of bags with seed and soil was similar to the Armidale experiment described previously. The same seed collected in December 2004 from the

Liverpool Plains of northern NSW and placed in the freezer was used for this experiment. Although the germination test to determine the dormancy and viability of seed was not performed, the first recovery from the burial trial showed that initial viability was very close to 100%. The soil in the experimental area was dug using a narrow shovel and the seed bags were buried at one of the three depths. The surface bag was anchored to the soil surface by a small iron rod bent over it (Figure 5.6).



Figure 5.6 *Lolium rigidum* germination from bags placed on the soil surface held down by the iron rod at the Tamworth Agricultural Institute.

For identification purposes, wooden pegs with aluminium tags were inserted next to each buried bag. Bags were buried in the soil 1 m apart to provide sufficient space for access between each burial site. The area was covered with plastic netting allowing the rain through, resting on iron posts to prevent entry of birds and rodents (Figure 5.5). The net was kept in position with the help of wooden logs around the base of the netting. Rodent bait was also installed inside the experimental area to avoid damage to the bags and the *L. rigidum* seed. Care was taken not to allow any of the bags to leak seed as the seed used in this burial experiment was glyphosate resistant seed and the field area surrounding the experimental site had no previous history of glyphosate resistant ryegrass. The experiment commenced on 23 March 2005. Total monthly rainfall and the mean monthly temperature during 2005 and 2006 are presented in Figure 5.7.

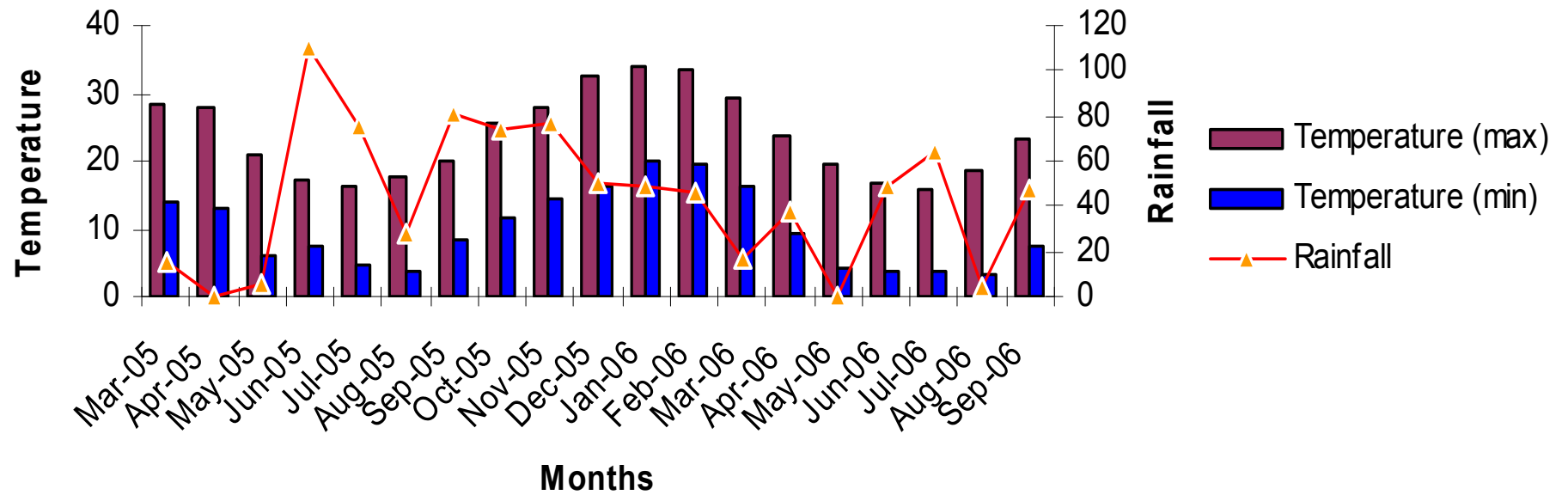


Figure 5.7 Total monthly rainfall (mm) and mean monthly temperature (max and min) during 2005 and 2006 at Tamworth.

Seed exhumation

Twelve bags were exhumed on each occasion (four replicates x three depths). After exhumation, seeds were separated from the soil using the same dry sieving method, and germinated in petridishes and tested for dormancy using tetrazolium chloride, as in the Armidale experiment.

There were four data sets available from this trial. They were:

- a. Viable seeds = germinable viable + dormant viable seeds;
- b. germinable viable seeds;
- c. dormant viable seeds; and
- d. dead seeds (germinated or emerged in field) = total seeds in bag (50) – number of viable seeds (germinable seeds + dormant seeds).

Seedling field emergence

Seedling emergence in the field was not counted in this experiment as the trial was located well away from the University campus, and could not be monitored as regularly.

Data analysis

Data were analysed using the S-Plus 2000[®] package. Means and standard errors were calculated and represented as bar plots to compare treatment differences. *P* values were calculated using the GLMs to determine significance levels. The responses varied irregularly over time and were therefore compared using standard error bar plots.

5.3. Results

Armidale experiment

The initial viability tests before the start of the main experiment showed that of the glyphosate resistant *L. rigidum* seeds sown, 53% seeds were germinable, 35% were viable but dormant (total viability of 88%), and the remaining 12 % were dead.

Viable seeds

The sum of germinable and dormant seeds represents the total number of viable seeds. They are represented as a percentage of the total seeds in each bag (50). The four way analysis of deviance indicated that the three way interaction of exhumation time x depth x soil, exhumation time x rainfall x soil, the two way interactions of rainfall x soil, exhumation time x soil and 'soil', 'rainfall' and 'exhumation time' of the main terms were highly significant in affecting the number of viable seeds. All the other main terms and interactions were not significant. The data were then fitted to a logistic regression model (Equation 5.1) and the a and b parameters used to interpret the change of viable seeds over time from each treatment combination.

Soil types had a pronounced effect on the viability of *L. rigidum* seeds over time (Figure 5.8). The seeds placed in the Kirby soil had greater viability over the 16 month period (but particularly in the initial stages) compared with those in the Laureldale soil. The greatest number of viable seeds (56%) was observed at 10 cm depth, 4 months after burial of the seeds under Tamworth rainfall pattern and Kirby soil (based on the mean values). The rate of reduction of viable seeds was also greater for all treatment combinations under the Kirby soil compared with Laureldale soil. The fastest rate of reduction of viable seed was observed in the Kirby soil with Tamworth rainfall and 10 cm depth ($b= 10.57$) compared with Laureldale soil ($b= 2.81$).

Viability was not only affected by soil type but by its interaction with rainfall type. Generally, in the Kirby soil, seed in the Tamworth rainfall pattern appeared to have a greater number of viable seeds (based on mean values and particularly in the initial stages) and greater rate of reduction of viable seeds over time compared with Hamilton. In contrast, under Laureldale soil, the Hamilton rainfall pattern had a greater number of viable seeds and greater rates of reduction of viable seeds compared to Tamworth.

Overall, the viability of *L. rigidum* seeds was not affected by varying burial depths. However, depth appeared to have significant affect under the Kirby soil. With the same Tamworth rainfall pattern, seeds placed at 10 cm depth had greater numbers of

viable seeds and rates of reduction compared with 5 cm depth ($b= 10.57$ and 5.8 respectively).

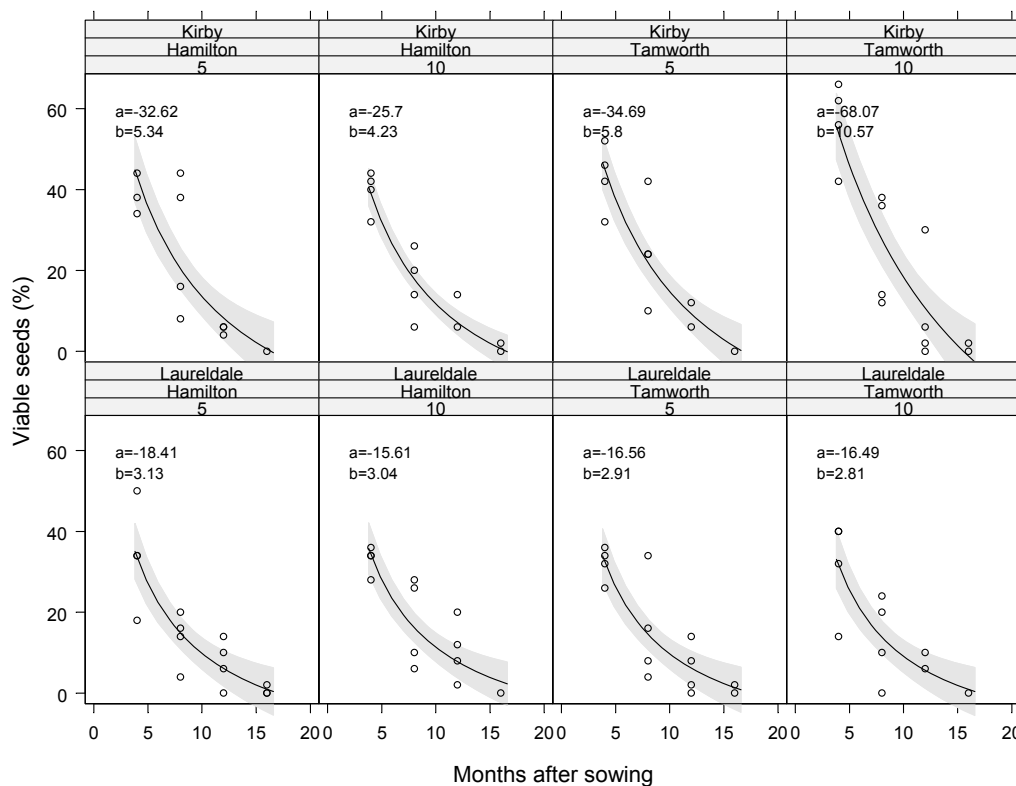


Figure 5.8 Percentage of viable *L. rigidum* seeds recovered from the experiment at Armidale. Data were fitted to an inverted Michaelis-Menten function (Equation 5.1) with 95% confidence limits shown. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. Soil types were clay (Laureldale) and sandy loam (Kirby); rainfall patterns were winter (Hamilton) and summer (Tamworth); burial depths were 5 and 10 cm. a = lower asymptote, b = rate of reduction.

Exhumation of seed bags from the pots over time showed changes in the viability of *L. rigidum* seeds. The greatest viability levels for all treatment combinations occurred at 4 months after seed burial. The number of viable seeds decreased rapidly over the 16 month period. From an initial level before the start of the experiment of 88%, viability decreased across all the treatment combinations to nil or very low numbers.

Germinable seeds

The seeds recovered from the bags at each exhumation time which germinated under controlled conditions were termed germinable seeds and are presented as a percentage of the total seeds in a bag (50) (Figure 5.9).

The four way analysis of deviance indicated that the four-way interaction of depth of burial x rainfall x soil type x exhumation time, three way interaction of exhumation time x rainfall x soil, two way interaction of depth x soil, exhumation time x depth, exhumation time x soil, exhumation time x rainfall and the main factor 'rainfall' were not significant, which suggests that the variation in the germination of *L. rigidum* seeds followed a similar trend for all these factors. All the other main terms and interactions were significant in affecting the germinability of seeds.

The data were then fitted to a logistic regression model (Equation 5.1) and the a and b parameters were used to interpret the change of germinable seed over time from each treatment combination (Figure 5.9).

Soil type had an effect on the germinable *L. rigidum* seed levels. Generally, there were more germinable seeds in the Kirby soil over the experimental period compared with the Laureldale soil and particularly in the early stages of the trial. This usually lead to a higher rate of deterioration of germinable seeds over the period of experiment. At 5 cm depth for Hamilton rainfall, Kirby soil promoted faster reduction of germinable *L. rigidum* seeds ($b= 0.93$) compared with Laureldale soil ($b= 0.75$). A similar trend was observed for seeds placed at 10 cm depth. However, at 5 cm depth and Tamworth rainfall pattern, the rate of reduction was similar between both soil types, whereas at 10 cm depth the Kirby soil again had higher germinable seed numbers early on and a higher rate of reduction ($b= 1.63$) compared with Laureldale soil ($b= 0.78$).

The winter (Hamilton) and the summer (Tamworth) rainfall pattern influenced the germinable *L. rigidum* seed levels over time. Generally, there were greater numbers of germinable seeds with Hamilton rainfall compared with Tamworth at 5 cm depth for both soil types (based on the mean values). In contrast, the numbers were generally lower in the Hamilton rainfall pattern for seeds buried at 10 cm depth. Seeds buried at 5 cm depth in Kirby soil and Hamilton rainfall pattern had a greater rate of reduction of germinable *L. rigidum* seeds ($b= 0.94$) compared with Tamworth rainfall ($b= 0.35$). A similar trend was followed for the Laureldale soil type. In contrast, seeds germinating at 10 cm depth in Kirby soil and Tamworth rainfall pattern had greater

rate of reduction of germinable *L. rigidum* seeds ($b= 1.62$) compared with Hamilton rainfall ($b=0.76$). A similar trend was followed for the Laureldale soil.

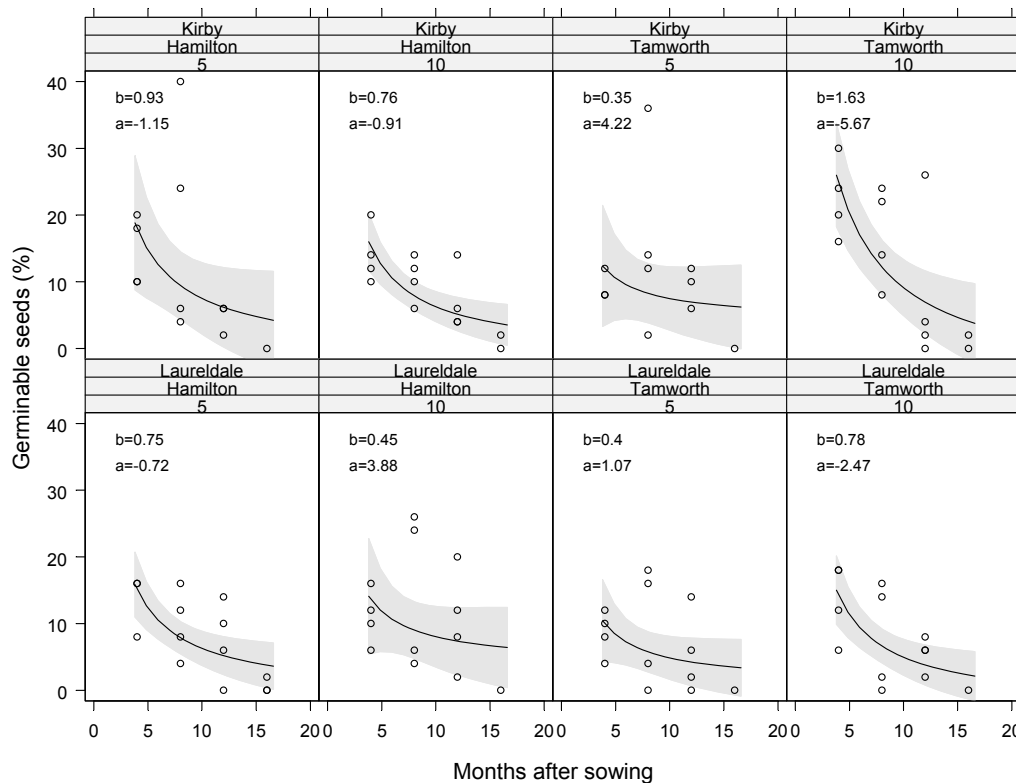


Figure 5.9 Percentage of germinable *L. rigidum* seeds recovered from the experiment at Armidale. Data were fitted to an inverted Michaelis-Menten function (Equation 5.1) with 95% confidence limits shown. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. Soil types were clay (Laureldale) and sandy loam (Kirby); rainfall patterns were winter (Hamilton) and summer (Tamworth); burial depths were 5 and 10 cm. a = lower asymptote, b = rate of reduction.

The germination of *L. rigidum* seed was greatly affected by varying soil burial depths. Under the Tamworth rainfall pattern, there were more germinable seeds in the early months at 10 cm depth for both soil types based on mean values. For Kirby soil and Hamilton rainfall, the rate of reduction was greater at 5 cm ($b= 0.94$) compared with 10 cm depth ($b= 0.76$). A similar trend was observed with Laureldale soil. Conversely, for Tamworth rainfall with Laureldale and Kirby soil types, a greater rate of reduction was found at 10 cm depth ($b= 1.63$) compared with 5 cm ($b= 0.35$).

The number of germinable seeds decreased gradually over the 16 month period. The initial germination percentage of seeds before the start of the experiment of 53%

decreased to varying degrees under different treatment combinations. Based on the mean values, the greatest decrease in the percentage of germinable seeds at 4 months of exhumation time was in Kirby and Laureldale soil at 5 cm depth and receiving Tamworth rainfall (down to 9%) and the least reduction occurred in Kirby soil at 10 cm depth and receiving Tamworth rainfall (22.5%). The rate of decline over the months was greater with Tamworth rainfall at 10 cm depth for both Kirby ($b= 1.62$) and Laureldale soil ($b= 0.78$). The lowest rate of reduction over the months was reported with Kirby soil receiving Tamworth rainfall at 5 cm depth ($b= 0.35$). The number of germinable seeds at 16 months exhumation time was reduced to zero or very low levels for most of the treatment combinations.

Dormant seeds

The non germinable seeds recovered from the growth cabinets and found to be viable after performing the tetrazolium tests were termed as dormant seeds. The dormant seeds are represented as a percentage of the total seeds in a bag (50) (Figure 5.10).

The four way analysis of deviance indicated that the three way interaction of exhumation time x rainfall x soil, two way interaction of exhumation time x rainfall and exhumation time, rainfall and soil of the main terms were significant. All the other main terms and interactions were not significant. The data were then fitted to a logistic regression model (Equation 5.1) and the a and b parameters used to interpret the change of dormant seeds over time from each treatment combination (Figure 5.10).

Soil types significantly affected the dormancy of *L. rigidum* seeds over time. Overall, the Kirby soil appeared to have significantly greater % of dormant seeds compared with the Laureldale soil at all four exhumation times (based on the mean values). Associated with this, the rate of reduction of dormant seed numbers was significantly greater in the Kirby soil (higher b values) compared with the Laureldale soil.

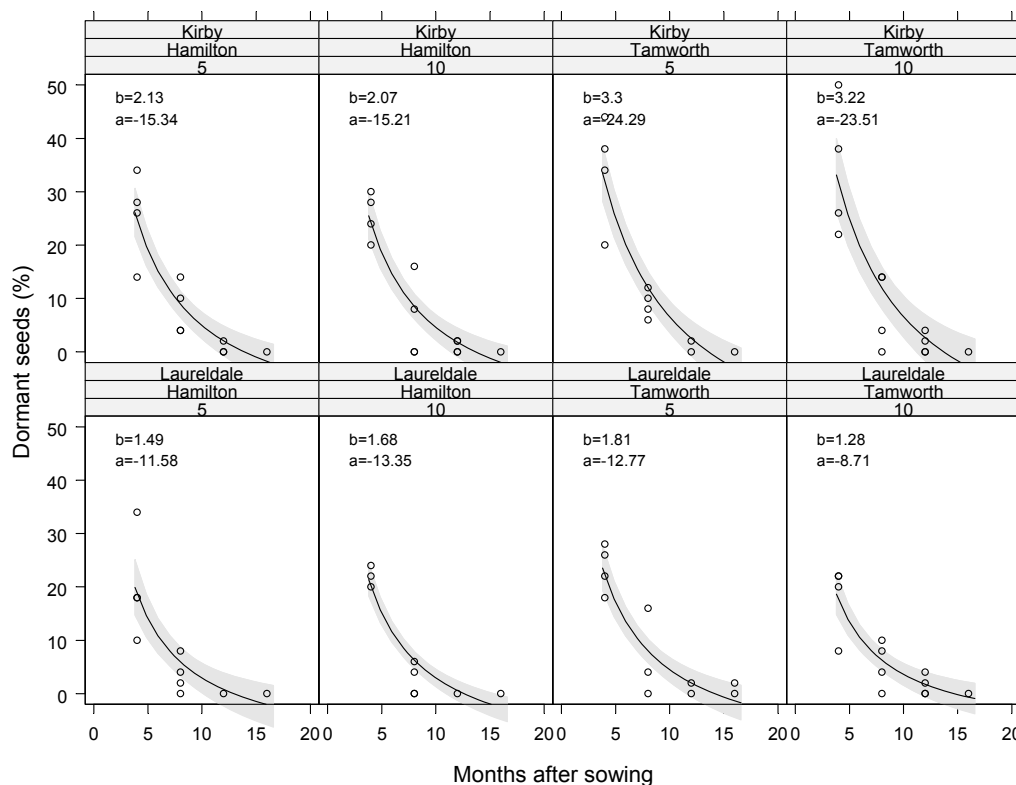


Figure 5.10 Percentage of dormant *L. rigidum* seeds recovered from the experiment at Armidale. Data were fitted to an inverted Michaelis-Menten function (Equation 5.1) with 95% confidence limits shown. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. Soil types were clay (Laureldale) and sandy loam (Kirby); rainfall patterns were winter (Hamilton) and summer (Tamworth); burial depths were 5 and 10 cm. a = lower asymptote, b = rate of reduction.

The rainfall pattern significantly affected the dormancy of *L. rigidum* seeds over time (Figure 5.10). In general, under Tamworth rainfall the percentage of dormant seeds was greater over the period of 16 months as compared with the Hamilton rainfall pattern. The rate of reduction over time of dormant seeds was likewise greater for the Tamworth rainfall pattern (higher b values) where there were higher dormant seed numbers compared with the Hamilton pattern, except for Laureldale soil at 10 cm depth, where the rate of reduction was greater with Hamilton ($b= 1.67$) compared with Tamworth ($b= 1.27$).

Depth did not affect the dormancy of *L. rigidum* seeds significantly over time. Correspondingly, the depth treatments appeared to have no major effect on the rate of reduction of *L. rigidum* seeds over time. However, the effects of exhumation times were significant. The number of dormant seeds decreased with increasing exhumation time from 4 to 16 months. The initial dormancy rate at start of the experiment was

35%. Four months after burial of seeds, the greatest reduction in dormancy was observed at 10 cm depth (down to 18%) in the Laureldale soil receiving Tamworth rainfall, with the lowest being in the Kirby soil (34%) at both the depths and Tamworth rainfall.

Emergence over time

Emergence was defined as the number of seedlings which emerged in the pots during the 16 month period. The results are represented as a percentage of the seedlings at 5 different times (2, 4, 5, 14 and 15 months) which emerged from the total seeds in a bag (50) (Figure 5.11). The four way ANOVA for the experiment showed that all the main terms except for rainfall, i.e. depth, soil and exhumation time were highly significant in affecting the emergence of *L. rigidum* seeds. All interactions were not significant.

The percent emergence of *L. rigidum* seedlings over different exhumation times are presented in Figure 5.11. Soil type influenced the emergence of *L. rigidum* seedlings; emergence was greater under the Laureldale soil than the Kirby soil. For example, in the Laureldale soil with Hamilton rainfall pattern seedling emergence was 50 and 77% greater at 5 and 10 cm compared with the Kirby soil (based on the mean values). Seed germinating in the Laureldale soil with Tamworth rainfall pattern at 5 cm and 10 cm depth had 63 and 82% higher emergence compared with the Kirby soil.

The depth of burial had a significant effect on the emergence of *L. rigidum* seedlings over time. The numbers of seedlings emerging from the seeds buried at 5 cm depth for both the Laureldale and Kirby soils were higher than at 10 cm depth.

Maximum emergence of *L. rigidum* seedlings was recorded in the first 2 months of burial for all the treatment combinations. Thereafter, few seedlings emerged up until about 12 months later. With the Laureldale soil, there were few emergences recorded up to 4 and 5 months followed by zero emergences up to 13 months of burial. In the 14 month, the number of emergences increased dramatically and later decreased again at 15 months. In contrast, the Kirby soil induced most emergences after 2 and 4 months of burial with decreased levels in the following months. With the Tamworth rainfall, there was a small peak of emergence at 14 months whilst at 15 months, there

appeared to be no emergence under Kirby soil, with a few emergences with the Laureldale soil.

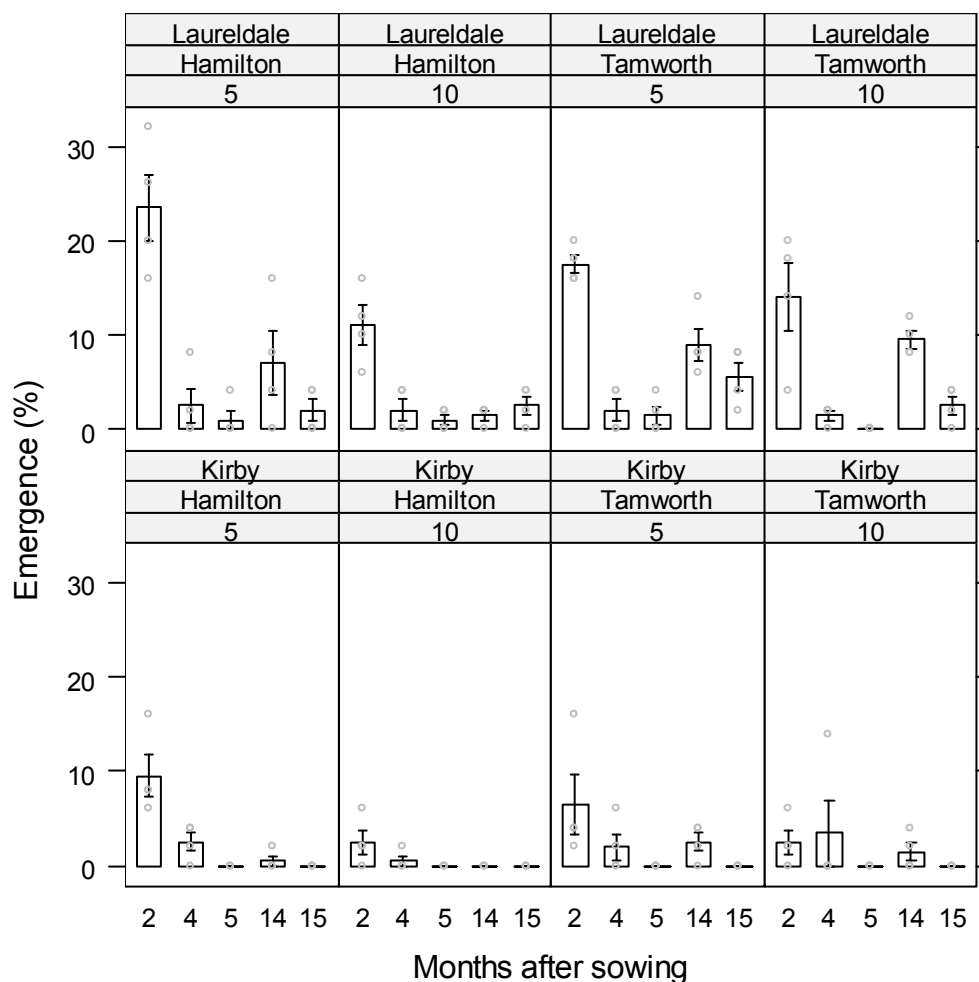


Figure 5.11 Percentage emergence of *L. rigidum* seeds in pots recorded at 2, 4, 5, 14 and 15 months at Armidale. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment. Soil types were clay (Laureldale) and sandy loam (Kirby); rainfall patterns were winter (Hamilton) and summer (Tamworth); burial depths were 5 and 10 cm.

Total emergence

Total emergence of *L. rigidum* seedlings represents the sum of emerged seedlings in the pots over the 16 month period and is represented as a percentage of the total seeds in a bag (50) (Figure 5.12).

The three way ANOVA table indicated that of the main terms, except rainfall, depth and soil were highly significant in affecting the total emerged number of seedlings. All interactions were not significant.

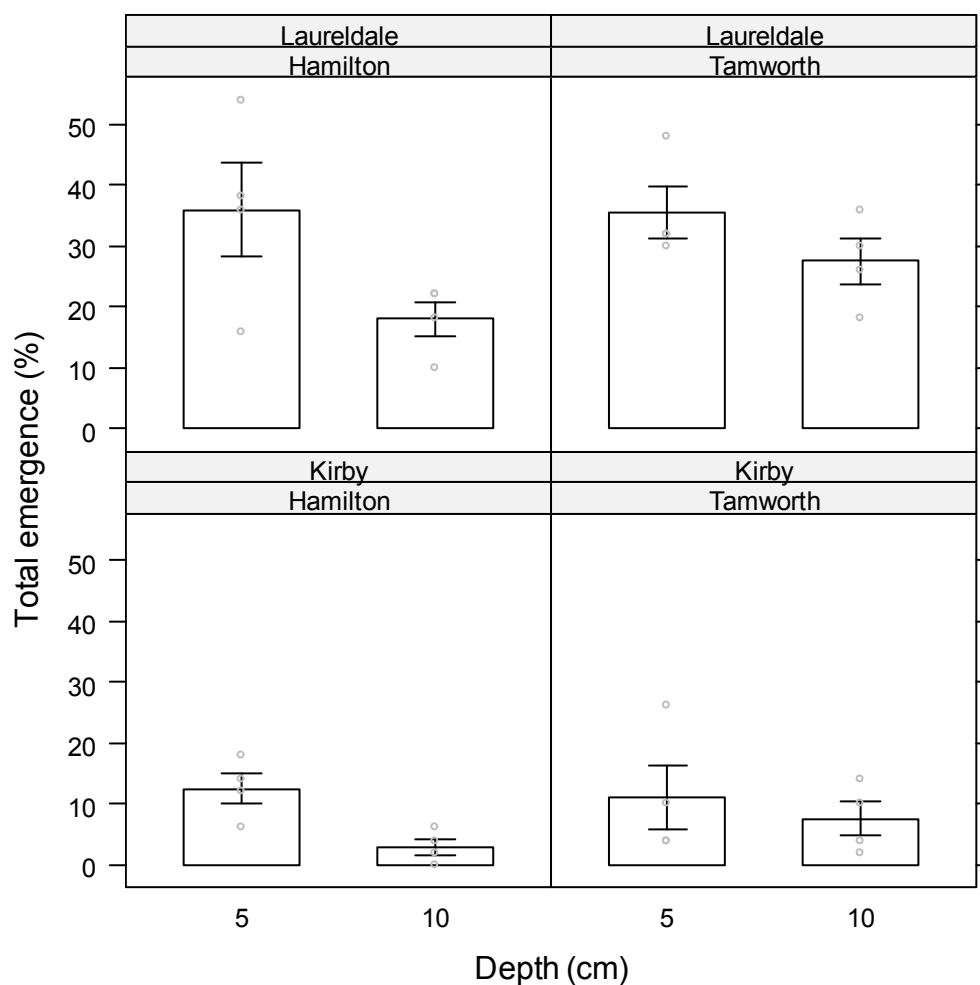


Figure 5.12 Percentage total emergence of *L. rigidum* seeds over 16 months in the experimental pots at Armidale. The vertical columns represent the mean values of individual treatment and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment. Soil types were clay (Laureldale) and sandy loam (Kirby); rainfall patterns were winter (Hamilton) and summer (Tamworth).

More seedlings emerged from the Laureldale soil than the Kirby soil (Figure 5.12). The total emergence in the Laureldale soil at 5 and 10 cm depth with Hamilton rainfall was 24 and 15% greater than in the Kirby soil respectively. Similarly, with Tamworth rainfall, emergence was greater with the Laureldale soil by 25 and 20% at 5 and 10 cm depths respectively.

Total emergence declined with an increase in burial depth from 5 to 10 cm for all treatment combinations. The greatest total emergence was from 5 cm depth in the Laureldale soil for both rainfall types. The lowest total emergence was reported at 10 cm depth in the Kirby soil with Hamilton rainfall.

Dead Seeds

The number of seeds which were unable to germinate in the growth chambers (other than dormant seeds) and the seeds which were not recovered from the bags or which were recovered germinated are defined here as dead seeds. They are represented as a percentage of the total seeds in a bag (50) (Figure 5.13).

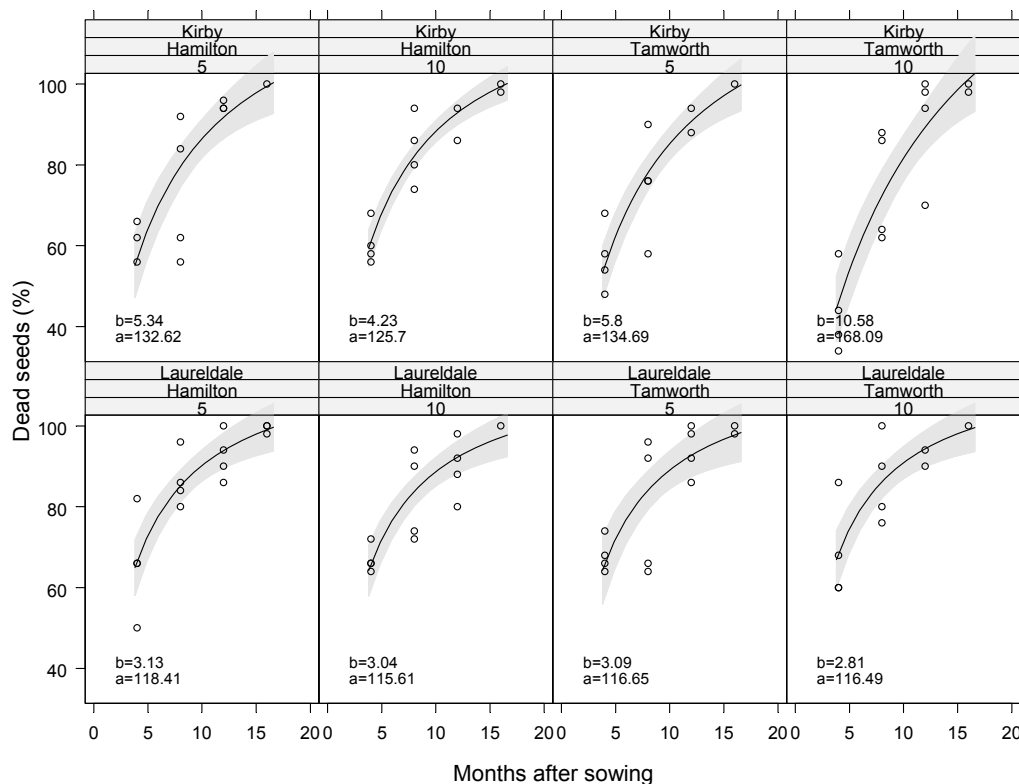


Figure 5.13 Percent dead (unviable recovered + missing + germinated) *L. rigidum* seeds at Armidale. Data were fitted to a Michaelis-Menten function (Equation 5.2) with 95% confidence limits shown. The shaded area represents the upper and lower confidence intervals. Hollow circles represent the replicate values of each treatment. Soil types were clay (Laureldale) and sandy loam (Kirby); rainfall patterns were winter (Hamilton) and summer (Tamworth); burial depths were 5 and 10 cm. a = upper asymptote, b = rate of increase.

The four way analysis with GLM indicated that the two-way interaction of exhumation time x soil and of the main terms, soil and exhumation time were highly significant in affecting the number of dead seeds over time. All other interactions and main terms, were not significant. The data were then fitted to a logistic regression model (Equation 5.2) and the a and b parameters were used to interpret the change of dead seed numbers over time for each treatment combination (Figure 5.13).

Soil type strongly influenced the increase in number of dead seeds over time. Laureldale soil had higher number of dead seeds as compared with the Kirby soil in

all the treatment combinations and particularly in the early stages of the trial. As a result, the rate of increase was higher in Kirby soil for all the treatment combinations. The greatest rate of increase was observed at the 10 cm depth with the Tamworth rainfall pattern ($b=10.58$).

Exhumation time also played a significant role in affecting the change in the number of dead seeds. The number of dead seeds increased strongly with increase in exhumation time from 4 to 16 months. The strong rate of increase was observed in the case of the Kirby soil at 10 cm depth and Tamworth rainfall ($b= 10.57$). At 16 months exhumation time, all the *L. rigidum* seeds appeared to be dead as most of the seeds had germinated by this time.

Tamworth experiment

Viable seeds

The two way GLM for this experiment indicated that of the main terms, only exhumation time was significant in affecting the viability of seeds (germinable + dormant) over time. None of the other main terms or interactions were significant.

Although depth was not significant in affecting the viability of seeds, it is worth noting the more rapid reduction in the number of viable seeds with the surface placement (seed at 4 months) compared with the 5 and 10 cm depths (Figure 5.14). Viable seed numbers were reduced to virtually zero after 18 months burial time at all three depths.

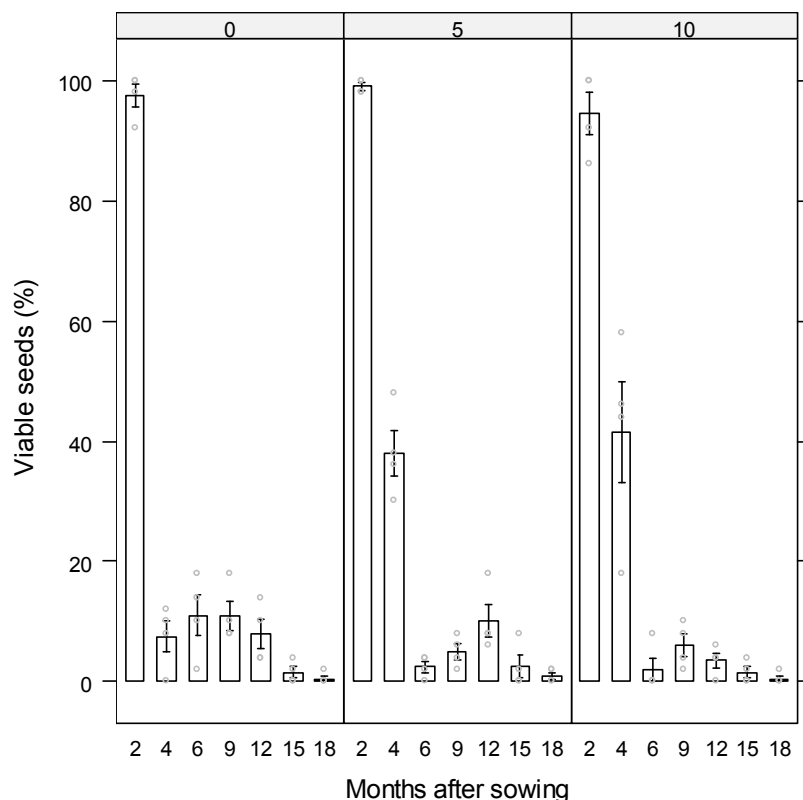


Figure 5.14 Percentage viable *L. rigidum* seeds recovered from the experiment at Tamworth. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate value of each treatment. Burial depths were 0, 5 and 10 cm.

Germinable seeds

The two way GLM for the experiment indicated that the two way interaction of depth x exhumation time and of the main term exhumation time were highly significant in affecting the germinability of *L. rigidum* seeds. The depth effect was not significant.

Percent germinable *L. rigidum* seeds over the 18 month period are presented in Figure 5.15. At 2 months, seeds placed on the surface soil had significantly greater (92.5%) germinable seeds compared with 5 cm (79.5%) and 10 cm depths (78.5%). At the 4 months exhumation time, higher numbers of germinable seeds were observed at 5 cm (30.5%) and 10 cm (33.5%) depths, than on the soil surface (2.5%). After 18 months of burial, there were nil or minimal levels of germinable seed observed at all the three soil depths.

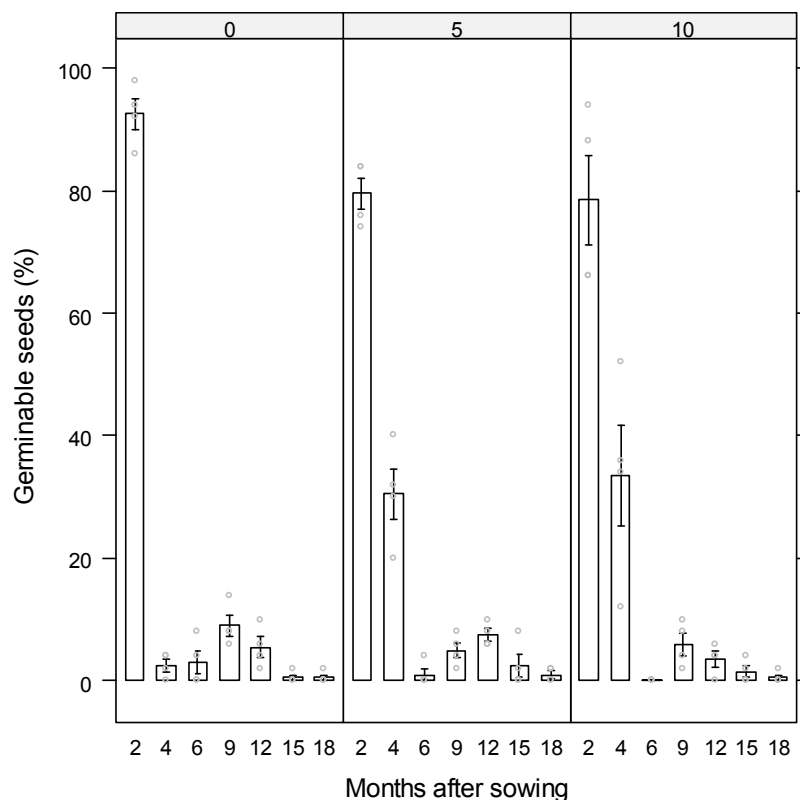


Figure 5.15 Percentage germinable *L. rigidum* seeds recovered from the growth chambers at Tamworth. The vertical columns represent the mean values of individual treatment and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment. Burial depths were 0, 5 and 10 cm.

Dormant seeds

The two way GLM for the experiment indicated that the two way interaction of depth x exhumation time and the main term exhumation time were highly significant in affecting the dormancy of *L. rigidum* seeds.

Percent dormancy of *L. rigidum* seeds over the 18 month period are presented in Figure 5.16. There were no significant differences found in the number of dormant seeds buried at 5 cm and 10 cm depth at most of the exhumation times. However, there were significant differences between seeds placed on the surface of soil and at the other two depths, especially after 2 and 6 months of burial ($P= 0.001$). At 2 months exhumation time, the surface seeds had only 5% dormant seeds, whereas burial induced dormancy so that at 5 cm depth (19.5%) and 10 cm depth (16%) there were higher levels of dormant seeds. Although the level of dormancy declined rapidly

at 5 and 10 cm depth, a low level of dormancy continued for the surface seed. By 18 months, none of the three depths appeared to have dormant seeds.

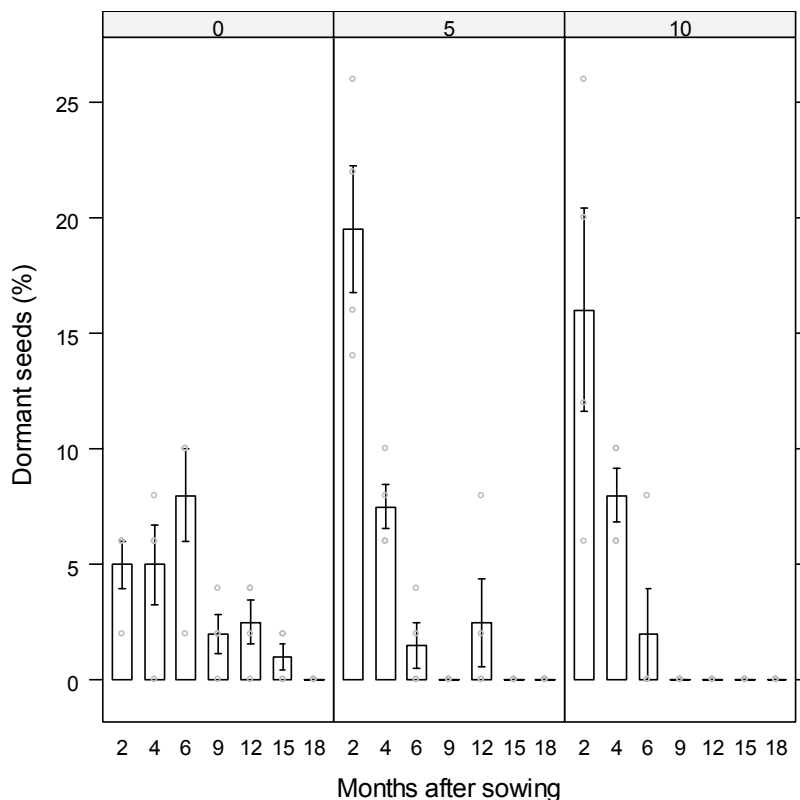


Figure 5.16 Percentage dormant *L. rigidum* seeds recovered from the experiment at Tamworth. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment. Burial depths were 0, 5 and 10 cm.

Dead seeds

Percentage dead seeds for *L. rigidum* are presented in Figure 5.17. The two way GLM showed that the two way interaction of exhumation time x depth and exhumation time of the main terms were highly significant. The variation in the number of dead *L. rigidum* seeds for depth alone was not significant. Very few seeds germinated or died in the first 2 months after burial at any of the depths but the numbers increased dramatically by 4 months after burial. At 0 cm the number of germinated and dead seeds increased to over 90%, whereas germination and death was delayed at 5 and 10 cm depths. At 4 months the values were 62 and 59% at the 5 and 10 cm depth respectively. By 18 months after burial, all the *L. rigidum* seeds were germinated or dead at all the depths.

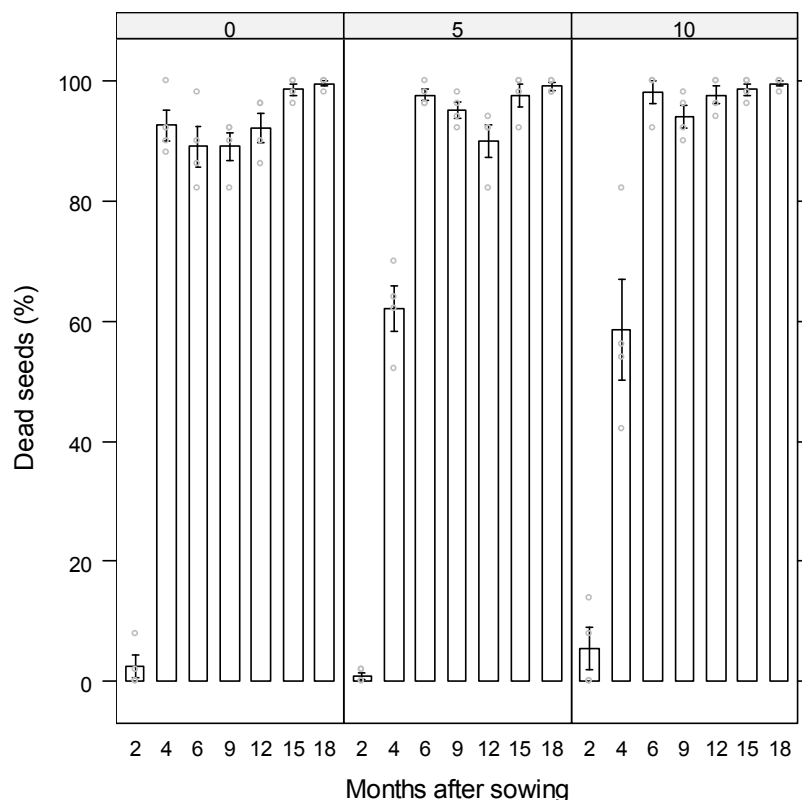


Figure 5.17 Percent dead (unviable recovered + missing + germinated) *L. rigidum* seeds at Tamworth. The vertical columns represent the mean values of individual treatment and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment. Burial depths were 0, 5 and 10 cm.

5.4. Discussion

The aim of the experiment at Armidale was to determine whether factors such as soil type, rainfall pattern, depth of burial and duration of burial affect the viability, dormancy and emergence of *L. rigidum* seeds. The aim of the experiment at Tamworth was to determine how factors such as depth of burial and duration of burial affect the dormancy and viability of *L. rigidum* seeds under field conditions.

Time

The number of germinable and viable seeds decreased gradually over the 16 month period at Armidale. More seeds germinated over time, which decreased the presence of any germinable and recoverable viable seeds. Kirby (sandy) soil was associated with greater levels of dormant seeds with the maximum numbers of dormant seeds recorded at 4 months after sowing. The *L. rigidum* seeds gradually lost dormancy over

time with zero dormant seeds recorded at the end of 16 months burial period. Results are supported by the findings of Peltzar and Matson (2002) who reported that *L. rigidum* seedbank declined at a rate of 70 to 80% per annum while *A. fatua* declined by 80% in the first year but only 50% in the second. Due to loss of dormancy, there were no viable or germinable seeds left in any of the pots and correspondingly at 16 months all the *L. rigidum* seeds were dead. Over the months, *L. rigidum* seeds gradually either lost dormancy and germinated or died due to factors such as predation or seed deterioration. Cheam and Lee (2005) observed greater percentage of loss of viable *L. rigidum* seed at Chapman Valley in Western Australia after 2 years of burial of seeds varying with depths. Greater percent loss were mainly observed at greater depth. At Mt. Barker, the loss was 15 (0 cm depth), 9 (1 cm depth), 9.3 (5 cm depth), 7.0 (10 cm depth) and 7.7 (15 cm depth) percent.

At Tamworth after 2 months of seed burial in 2005, there was no germination of seed in the field due to low rainfall (Figure 5.7). This was reflected in high numbers of viable and germinable seeds in the growth cabinet. However, in June and July 2005 sufficient rainfall was received to trigger the germination of *L. rigidum* seeds. Most of the seeds placed on the soil surface germinated during this time and so the recovered bags were left with few viable seeds.

Emergence decreased over time from 1 to 16 months. Fewer seedlings emerged in the second year compared with the first year. At 15 months, there were nil emergences reported for most of the treatment combinations. By this time most of the *L. rigidum* seeds had either emerged, germinated or died possibly due to the action of micro organisms or insect predation.

Soil

The greatest percentage of germinable seed was found at 4 months after burial of bags for both the soil types. The glyphosate resistant *L. rigidum* seeds placed in the clay soil (Laureldale) lost their dormancy faster than those placed in the sandy soil (Kirby) and thus had a lower number of viable and germinable seeds. Correspondingly, the Laureldale soil had a higher number of dead seeds at each of the exhumation dates as compared with the Kirby soil. This may be due to the Laureldale soil having a clay texture and containing greater organic matter which tends to have higher water

holding capacity. In contrast, the Kirby soil with a greater proportion of sand and less organic matter had poor water holding capacity, inducing lower germination levels. Greater *Melaleuca quinquenervia* germinations were found in clay soils (Van *et al.* 2005). These results are in contrast to those of Benvenuti (2003) and Quail and Carter (1968) who found that the soil with a pronounced clay matrix impeded the germination of buried seeds and induced seed dormancy in certain weed species. However, Benvenuti *et al.* (2001) suggested that it is difficult to compare results obtained in their study with those reported by other authors because of possible differences in dormancy characteristics of various species used, particular temperature and humidity conditions, and above all, the different soil characteristics.

The emergence was greater in the Laureldale soil than the Kirby soil. The maximum emergence occurred at 2 months after burial of bags; this then gradually decreased and this pattern was similar for both soil types. It appears that the greater proportion of seeds germinated in an initial first flush when favourable conditions prevailed. The results found at Tamworth are specific to those for dark reddish brown dry light clay common in that area.

Rainfall

The rainfall distribution pattern interacted with soil type, affecting the viability of *L. rigidum* seeds. Under summer rainfall (Tamworth), the *L. rigidum* seeds had greater viability than with the Kirby soil. However, under the winter rainfall treatment (Hamilton), Laureldale soils were associated with higher viable seed levels. Correspondingly, pots receiving the Tamworth rainfall were left with greater dormant seed levels as compared with the Hamilton rainfall. The dormancy was highest during the first 4 months of exhumation time when the Tamworth rainfall regime was drier than Hamilton and thereafter it was reduced to zero by the termination of the experiment. After 4 months of seed burial i.e. during July, 2005, the greater moisture levels in pots receiving the Hamilton rainfall pattern (Figure 5.1) and Laureldale soils created too wet conditions resulting in lower germinations and greater non germinated viable seed numbers. However, during July, 2005, pots receiving the Tamworth rainfall pattern were associated with lower moisture and lower germinations in Kirby soils. The probable reason may be that Kirby soils have poor water holding capacity and low organic matter which reduced the germination of *L. rigidum* seeds and caused

there to be higher levels of viable seeds. The lowest levels of *L. rigidum* viable seed numbers at individual times were associated with summer rainfall and the Laureldale soil and winter rainfall with the Kirby soil.

The glyphosate resistant seeds largely emerged over the first 4 months and then in months 14 and 15 after burial of bags i.e. April to July 2005 and May and June, 2006 respectively. Maximum emergence during both years occurred during mid autumn, which provided favourable temperature conditions (Figure 5.3) for *L. rigidum* to germinate and emerge, despite rainfall pattern varying between pots. *Lolium rigidum* seedlings emerged mainly from the seeds buried at 5 cm depth. Similar results were reported by Benvenuti *et al.* (2001) for *Rumex obtusifolius*, and Cheam and Lee (2005) and Gramshaw and Stern (1977) for *L. rigidum*. The Tamworth specific rainfall may have impacted on germination, viability and dead seeds and therefore the results found at Tamworth are specific to this area.

Depth

Depth of burial interacted with the rainfall pattern and exhumation time to have a pronounced effect on the germinable *L. rigidum* seeds at Armidale. At 4 months after burial, pots receiving Hamilton rainfall did not show differences in germination percentage at 5 and 10 cm depths. But, the pots with Tamworth rainfall pattern showed depth effects. The seeds placed at 10 cm depth achieved greater germination levels compared with 5 cm for both soil types. The probable reason may be due to increasing depth, as the seed germination % was lower at 10 cm depth resulting in greater viable seeds. Thus, there were greater germinations in the growth chambers of non germinated viable seeds. Inhibition of germination due to soil depth has been reported by many authors e.g. by Holm (1972), Stoller and Wax (1973) and Benvenuti and Macchia (1995, 1997). Correspondingly the total emergence was greater with seeds growing at 5 cm depth than at 10 cm depth. Dormancy of *L. rigidum* seeds was not affected by the depth of burial. Zorner *et al.* (1984b) working at Colorado, USA found that buried populations of dormant and non-dormant *Avena fatua* seeds persisted less than 2 years, with the depth of burial having very little influence on their survival.

At Tamworth, there was little germination observed from seeds placed at 5 and 10 cm depth. Less rainfall experienced was possibly stored as residual moisture at 5 and 10 cm depth which could later trigger the germination of *L. rigidum* seed. Correspondingly, a greater number of non germinated seeds were recovered from bags to germinate in the growth chambers from these depths. Rainfall played a pivotal role at 4 months exhumation time as most of the *L. rigidum* seeds lying on the surface were able to germinate due to adequate scattered rainfall received during June and July, 2005 (Figure 5.7). Similarly, at 2 months exhumation time, lower numbers of dormant seeds were recovered from the soil surface as compared with 5 and 10 cm depth. Similarly low numbers of seeds were found at the surface by Benvenuti *et al.* (2001) for *Rumex obtusifolius* and by Mennan and Zandstra (2006) for *Veronica hederifolia*. Lower germination was similarly encountered with increased soil depth by Om *et al.* (2003) and Roberts and Feast (1972). However, at 6 and 8 months of exhumation time, greater numbers of dormant seeds were recovered from the bags placed at the soil surface and nil or very few dormant seeds from 5 and 10 cm depth. Again, the rainfall received in the 5 to 9 month period was likely to be sufficient to percolate deep in the soil and keep the soil moist at 5 and 10 cm depth and this is likely to have prompted greater germination of *L. rigidum* seeds. The surface soil on the other hand, may have become dry after the rainfall and unlike the deeper soil did not retain sufficient moisture for adequate germination.

Most of the seeds placed at 5 and 10 cm depth germinated by the 9 months exhumation period, apparently due to substantial amounts of rainfall received for their germination in previous months. Grace *et al.* (2002) concluded that at all depths, the most rapid decrease in seedbanks of *Carthamus lanatus* was in the first 6-month period. There were negligible numbers of dormant seeds recovered at the later months except at 5 cm depth with the 12 months exhumation time. At 18 months exhumation time, most of the seeds had either germinated or died at all the depths in the field and thus few non germinated seeds were recovered from the bags at the termination of the trial.

5.5. Conclusions

The following conclusions can be drawn concerning the effects of rainfall, soil type and depth of burial on the of *L. rigidum* seeds over time.

- In the short term, soil types affected germination but the longevity of *L. rigidum* seeds in either of the soil type did not extend beyond 18 months in either the pot experiment or field in the northern grain region.
- Rainfall influenced longevity via germination in the short term but differences between Mediterranean and summer dominant rainfall were not sufficient to alter overall longevity of seed. Therefore seed in this northern environment is likely to behave similarly to that in more southern areas at least in terms of longevity. For management, seed production needs to be stopped for at least 18-24 months to deplete the seedbank to zero on the Liverpool Plains.
- Depth of burial influenced germination and dormancy over the short term, but like rainfall, soil type and depth did not influence longevity of seed in the long term. In terms of management, deep burial from ploughing is unlikely to extend seed longevity beyond 18 months but will lead to loss of seed through death and germination (Chapter 7).

Chapter 6. Predicting seedling emergence

6.1. Introduction

The timing of weed emergence relative to the crop growth stage is critical in targeting and optimizing the timing of weed control (Cousens *et al.* 1987, Peters 1984). A better understanding of the emergence behaviour of weed species in relation to cultural and meteorological events, presents a number of opportunities for improved weed management (Grundy *et al.* 2003). This information could be used to target the timing of cultivation and maximise the efficacy of control strategies, regardless of whether by chemical or physical methods (Vleeshouwers 1997). Early weed emergence in relation to the crop, permits weeds to become established and compete better with crops. The magnitude of crop yield losses from crop-weed competition, among other factors, depends on the time of weed seedling emergence relative to that of the crop (Chikoye *et al.* 1995, Knezevic *et al.* 1997, Moechnig *et al.* 2003).

For example, Knezevic *et al.* (1997) reported that the time of redroot pigweed (*Amaranthus retroflexus*) emergence relative to the growth stage of sorghum (*Sorghum bicolor*), was critical to the outcome of sorghum-pigweed competition because significant sorghum yield losses occurred when redroot pigweed emerged before the five-leaf stage of sorghum.

There have been significant research developments in recent years aimed at understanding and predicting the emergence patterns for a number of important weed species (Grundy 2003). *Lolium rigidum* is economically significant in Australian agriculture and in recent years has developed resistance to glyphosate on the Liverpool Plains in northern New South Wales. The prediction of the emergence patterns of *L. rigidum* would be valuable in planning and implementing management strategies for this weed. Also unknown, is whether glyphosate resistance affects emergence patterns in comparison with susceptible *L. rigidum* and where cultivation is again incorporated to deal with herbicide resistant weeds, does seed burial affect prediction of emergence. Currently, weed management decisions aim to provide a weed free environment for crops during the critical early post-emergence period (Walsh *et al.* 2002).

WEEDDEM (Archer *et al.* 2002) is an interactive software package designed to predict the timing of emergence for two troublesome weeds of Western Australian dryland cropping regions: *Lolium rigidum* and *Raphanus raphanistrum*. WEEDDEM uses emergence models based upon Australian laboratory and field data. The software model predicts emergence based on microclimate conditions near the soil surface, relating these conditions to seed dormancy status and extent and timing of seedling emergence. Microclimate values are estimated based on weather inputs supplied by the user. It assumes that most of the seed is present in the top 0-2 cm soil.

Two experiments (one field, one pot) were initiated in 2005 and repeated in 2006 to compare the emergence of herbicide resistant and susceptible *L. rigidum* seeds. The herbicide resistant seeds were mainly resistant to glyphosate and some Group A and B herbicides (Andrew Storrie, New South Wales DPI; pers. comm.) whereas the herbicide susceptible seed was assumed to be susceptible to glyphosate and a range of other herbicides. The resulting data set were then used to explore and explain differences in the emergence behaviour of *L. rigidum* seeds under cultivated conditions to that predicted by the WEEDDEM model in Western Australia.

6.2. Methods

Sites

The field experiment was conducted at the University of New England's (UNE) Laureldale Research Station, Armidale, NSW, Australia (30° 30' S, 151° 40' E). The soil was medium heavy clay chocolate basalt (0-10 cm depth, pH 6.4, and 2.8% organic matter) and the trial ran over 2005 and 2006. The field used for the trial had not been cropped for the previous 3 years. The field was cultivated with chisel plough once, prior to the experiment being initiated. The trial was repeated in pots to cross check the emergence data. The trial was conducted in an open area on the UNE campus within 1 km of the field site, with no obstruction of wind, light and rainfall.

Treatments

The two treatments in both experiments were glyphosate resistant *L. rigidum* seed (HR) and glyphosate susceptible *L. rigidum* seed (HS). Herbicide resistant seed was collected in December 2004 from the Liverpool Plains in northern New South Wales

from a field with known herbicide resistance and the other seed lot considered as glyphosate susceptible was obtained from a local supplier originating from Victoria and used by pasture growers.

Design

The field trial comprised two treatments replicated four times in a Randomized Complete Block Design (RCBD) (Figure 6.1). The pot trial comprised of two treatments replicated eight times in a complete randomised design (CRD).



Figure 6.1 Counting and uprooting of emerged *L. rigidum* seedlings in the weed emergence field trial at Laureldale Research Station.

Initial viability test

A germination test was conducted to determine the initial percentages of germinable, dormant and dead seeds before the start of the experiments. The procedure followed was similar to that described in Chapter 5.

Field and pot operation

The field experiment consisted of eight main plots each of 1.4 x 1.4 m with 2 m buffers between blocks and 1 m buffer between plots within a block (Figure 6.1). *Lolium rigidum* seeds were broadcast on the soil surface at the rate of 500 seeds m⁻² and mixed in the soil to a maximum depth of 5 cm with a rake. Wheat (*Triticum aestivum*) was sown 5-7 cm deep in rows 20 cm apart by hand at a rate of 100 kg ha⁻¹. Sowing of both *T. aestivum* and *L. rigidum* occurred during 23 August 2005 and 28 August 2006; both species were sown on the same day one after the other and the crop was fertilized with broadcasted urea at the rate of 30 kg N ha⁻¹.

In the pot experiment, the pots (15 cm diameter) were filled with the same soil collected from Laureldale Research Station and 50 seeds of *L. rigidum* were broadcasted in each pot after filling of pots on the same day during both years with the field experiment. The seeds were mixed into the soil up to a maximum of 5 cm deep by hand after fertiliser application and left in the open for germination. Rainfall and temperature data were recorded at the field site (Figures 6.5 and 6.9).

Data collection

In both years and for both experiments, the emerged HR and HS *L. rigidum* seedlings were counted and uprooted on a weekly basis after the sowing operation. The counting and uprooting procedure was carried out until seedling emergence ceased in each of the plots/pots. The field was cultivated after harvesting the *T. aestivum* crop and left undisturbed until the next season. A different area adjacent to the previous years experiment was used for 2006 field trial to make sure that no residual *L. rigidum* seed was present in that part of field. After the termination of the pot trial in 2005, pots were filled with fresh soil for the 2006 trial.

Data entry into WEEDM

The average daily rainfall and minimum and maximum temperature data for 2005 and 2006 were entered into the WEEDM model as well as previous crop residue, soil type and moisture details. None of the data collected from either the pot or field trials was used by WEEDM for predictions. Predictions of *L. rigidum* emergences for the specified time period were produced graphically in the form of a curve after converting the rainfall and air temperature data into soil temperature, soil moisture and soil water potential.

Data analysis

The data for *L. rigidum* emergence in field and pot were analysed in R program (R Development Core Team 2006). *P* values were calculated using the ANOVA function to determine the effects of the treatments at individual time points. Treatments were compared using the standard error of means. Diagnostic plots were used to check the normality of the data for each response variable and homogeneity of variance. No transformations were necessary.

6.3. Results

The results from the preliminary germination test before the start of the experiments in 2005 showed that 90% of HR *L. rigidum* seeds were germinable, 6% were viable but dormant and the remaining 4% were dead. For the HS, 92% of seeds were germinable, 4% were dormant and 4% were dead. Before the start of the experiment in 2006, 92% of HR seeds were germinable, 2% were dormant and 6% were dead. For HS seed, 92% were germinable, 3% were dormant and 5 % were dead.

Field and pot experiments in 2005

The ANOVA of the field trial in 2005 showed that emergence of *L. rigidum* seedlings occurred at different times over the ‘weeks’ and that the weeks x treatment interaction was highly significant. The pot experiment had similar results except that the main term ‘treatment (resistant and susceptible *L. rigidum*)’ was found to be additionally significant.

Results obtained from the field trials in 2005 showed that, with the prevailing climatic conditions, HR *L. rigidum* seedling emergence was less than 5% after first week of sowing (Figure 6.2). Each of the second and third weeks experienced the greater part of emergences to a total of about 80%. After 4 weeks, total percentage emergence of *L. rigidum* was about 87% and the remaining 2% emerged in the last 2 weeks of data collection. However, unlike the HR seed, 22% of the HS seed emerged in the first week after sowing. The 2nd and 3rd weeks had 42 and 25% of seeds emerged respectively. The HS seed lot emerged to the level of about 90% in first 3 weeks. The remaining 5% emergence was observed in last 3 weeks of the germination cycle. After 6 weeks 88% emergence was observed in the HR seed and 93% emergence was observed in the HS seed. No further emergences were observed after 6 weeks.

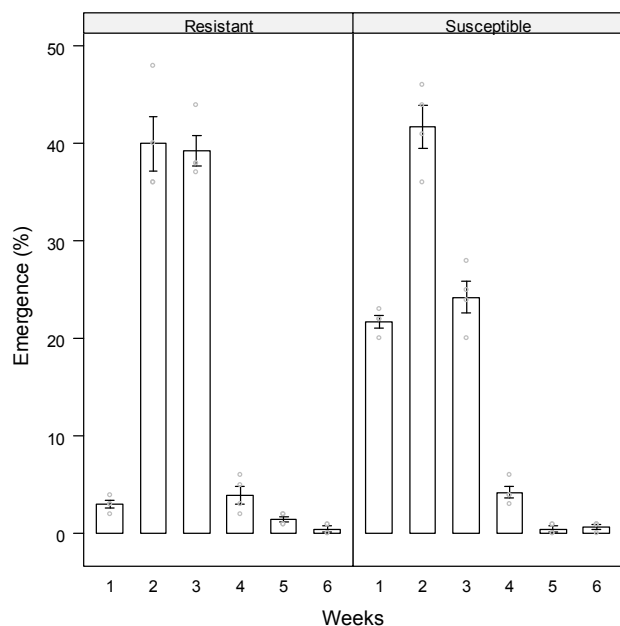


Figure 6.2 Weekly percent emergence of *L. rigidum* in the field at Laureldale Research Station during 2005. The vertical columns represent the weekly percentage emergence and the bars are the standard errors (\pm). Small circles represent the replicate values of each treatment. Resistant = HR, susceptible = HS

In the pot trial, HR *L. rigidum* seedlings were again slower to emerge than seedlings from HS seed (Figure 6.3). The first 4 weeks accounted for 82% of the HR seedling emergence followed by 1% emergence in 5th week. However, 87% of the HS seed lot germinated in the first 3 weeks, followed by few emergences in the 4th week. After 5 weeks 85% emergence was observed in the HR seed and 90% emergence observed in the HS seed. No further emergences were observed after 5 weeks.

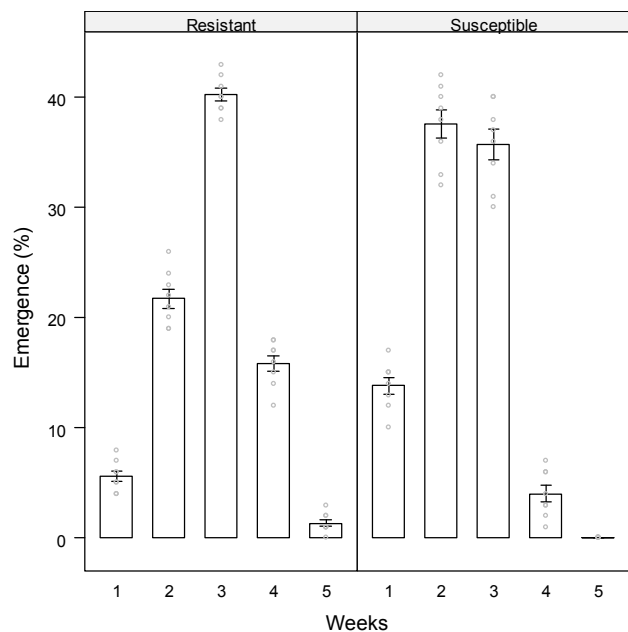


Figure 6.3 Weekly percent emergence of *L. rigidum* in pots at UNE campus during 2005. The vertical columns represent the weekly percentage emergence and the bars are the standard errors (\pm). Small circles represent the replicate values of each treatment. Resistant = HR, susceptible = HS

Predicted emergence by WEEDM in 2005

The predicted field emergence of *L. rigidum* seedlings by the WEEDM model for 2005 is shown in Figure 6.4. Predicted values suggested that the first week after sowing would be associated with about 55% *L. rigidum* emergence and by the end of the second week a total of about 98% of seedlings would be emerged and 100% emergence by week 4. The soil moisture during the first 2 weeks varied from 50 to 60% and there was nil precipitation except during the last 2-3 days of the second week. The emergences can be compared with the prevailing climatic conditions detailed for the time of emergence from Figure 6.5.

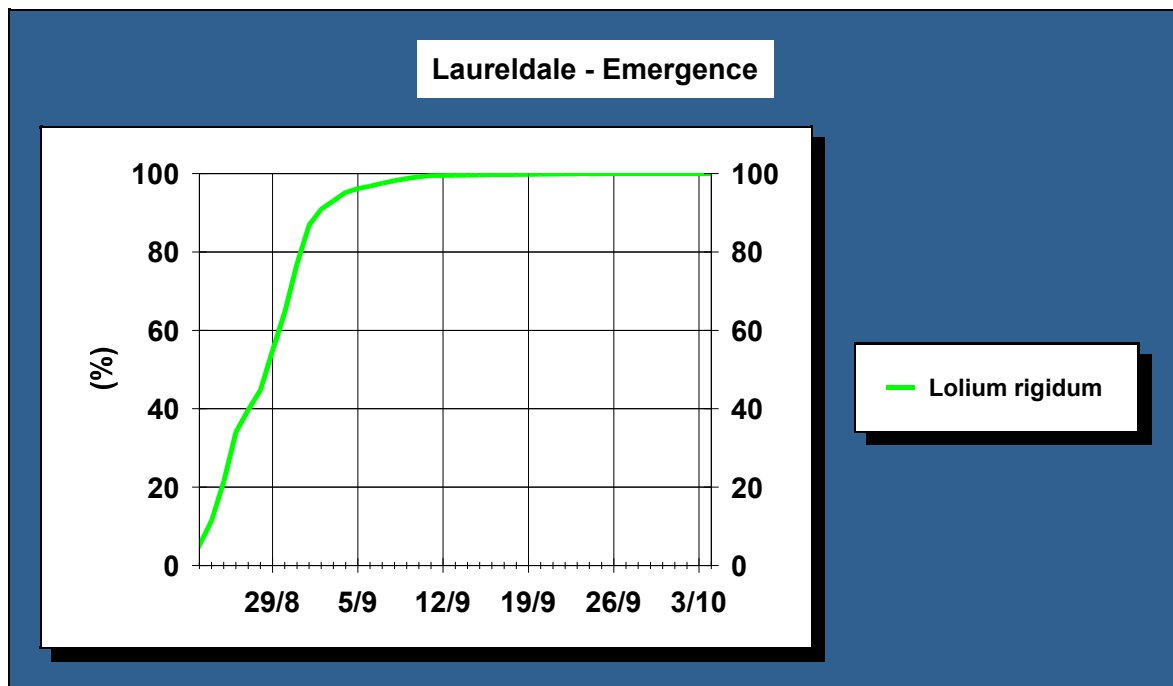
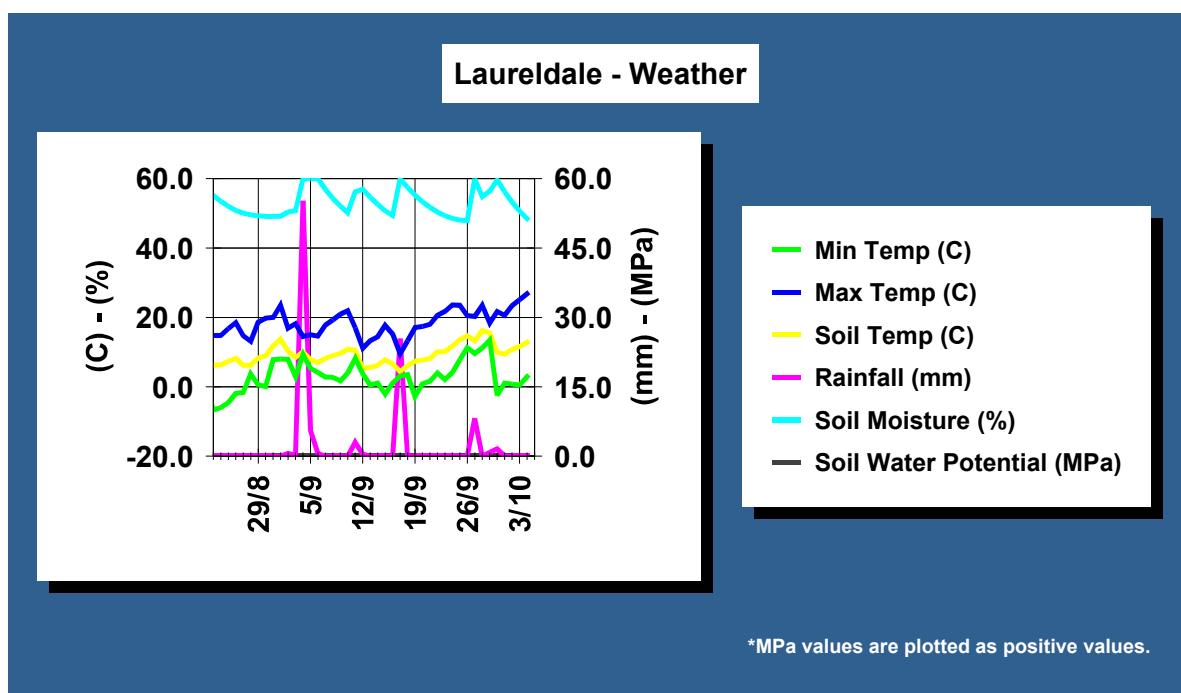


Figure 6.4 Predicted % emergence each week for *L. rigidum* by WEEDEM from late August to early October in 2005



*MPa values are plotted as positive values.

Figure 6.5 Meteorological values calculated in WEEDEM from late August to early October on the basis of rainfall and temperature data entered from Laureldale Research Station in 2005. C = °C

Field and pot experiments in 2006

The ANOVA of the 2006 field and pot trial show that seedlings emerge at different times over the ‘weeks’ and that the weeks x treatment (resistant and susceptible *L. rigidum*) interaction was highly significant.

In 2006 in the field HR *L. rigidum* seedling emergence was less than 4% after the first week of sowing (Figure 6.6). The second week had the greatest emergence (44%) followed by the third week (39%). Within 3 weeks, total percentage emergence of *L. rigidum* was about 86% and the remaining 4% emerged in the last 2 weeks of data collection. However, similar to 2005, the HS seed emerged more quickly, with 20% of emergences in the first week after sowing. The second and third weeks had 48 and 24% emergences respectively. The glyphosate susceptible seed lot emerged to a total of about 91% in the first 3 weeks, while the remaining 2% of seeds emerged in the last 2 weeks of the germination cycle. After 5 weeks, there was 90% emergence in the HR seed and 94% emergence in the HS seed. No further emergence was observed.

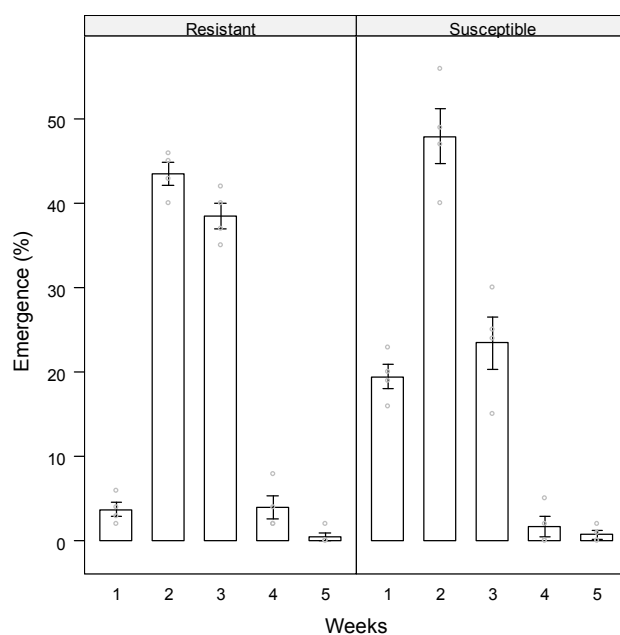


Figure 6.6 Weekly percent emergence of *L. rigidum* in the field at the Laureldale Research Station during 2006. The vertical columns represent the weekly percentage emergence and the bars are the standard errors (\pm). Small circles represent the replicate values of each treatment. Resistant = HR, susceptible = HS

In the pot trial, most HR *L. rigidum* seedlings emerged the in 2nd (17%), 3rd (32%) and 4th (25%) weeks after sowing (Figure 6.7). These 3 weeks accounted for a total of 74 % emergence followed by 6% in the 5th week totalling 84% emergence. However, the

HS seed mostly germinated (84%) in the first 3 weeks followed by few emergences in the 4th and 5th weeks totalling 88% emergence after 5 weeks.

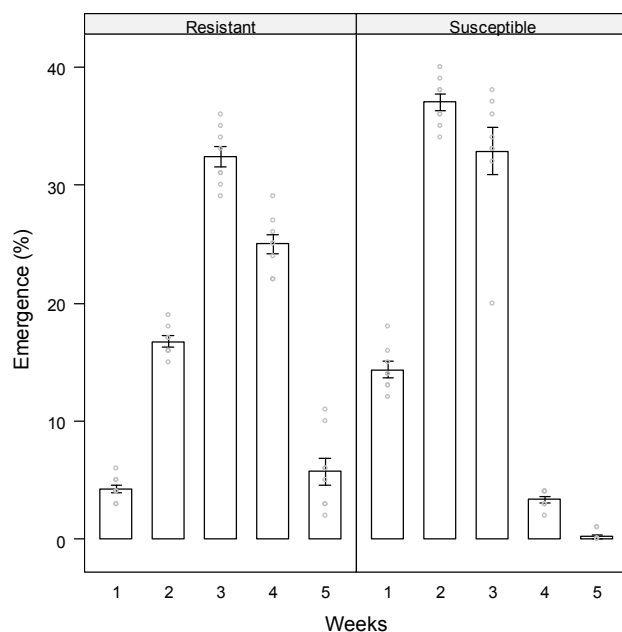


Figure 6.7 Weekly percent emergence of *L. rigidum* in the pots at UNE campus during 2006. The vertical columns represent the weekly percentage emergence and the bars are the standard errors (\pm). Small circles represent the replicate values of each treatment. Resistant = HR, susceptible = HS

Predicted emergence by WEEDM in 2006

The predicted emergence of *L. rigidum* seedlings by WEEDM model during 2006 are shown in Figure 6.8. WEEDM predicted that about 90% of *L. rigidum* seed would emerge in the first week after sowing and by the end of second week, a total of about 98% would have emerged. The soil moisture during first 2 weeks varied from 43 to 60% and there was some precipitation observed during the 2 week period. The emergences can be compared with the prevailing climatic conditions in detail at the time of emergence from Figure 6.9.

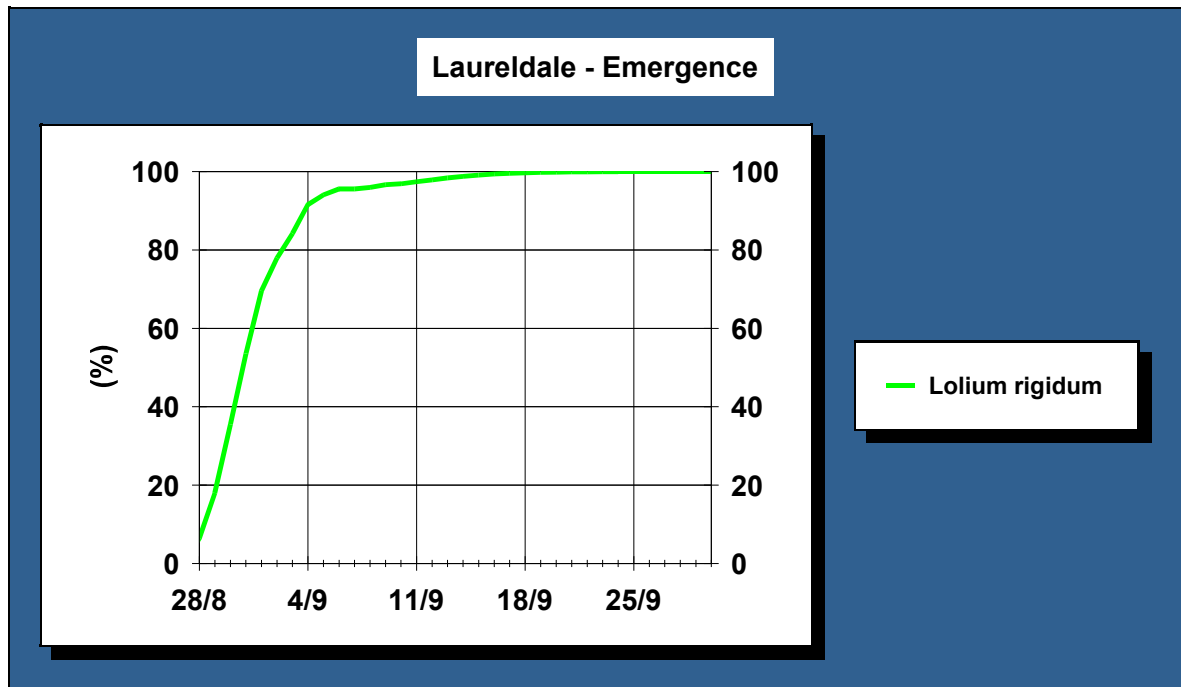


Figure 6.8 Predicted % emergence each week for *L. rigidum* by WEEDEM from late August to late September in 2006

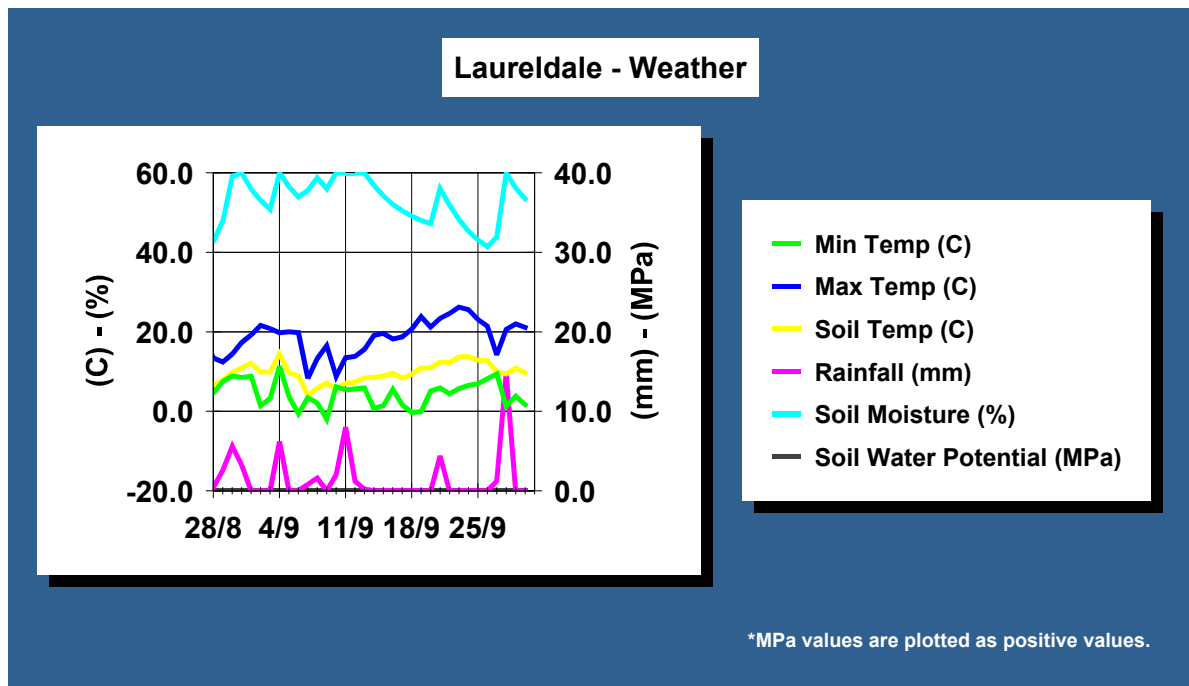


Figure 6.9 Meteorological values calculated in WEEDEM from late August to early October on the basis of rainfall and temperature data from Laureldale Research Station in 2006. C = °C

6.4. Discussion

Difference in emergence between HR and HS seed

In 2005 and 2006, only about 5% of HR *L. rigidum* seedlings emerged in the field during the first week of germination cycle however, there were about 20% emergences from the HS seed lot. The HR seed originated from the Liverpool Plains while the HS seed came from Victoria. The differences in emergence patterns may be due to a whole range of factors associated with the seed sources e.g. time at which they were harvested, location of growth and environmental conditions of ripening, biotype differences etc. The HS seed assumed as susceptible to glyphosate before the start of the experiment was actually found to be resistant to glyphosate and a range of other herbicides (Chapter 3). However, the level of resistance in HS seed was not as high compared with the HR seed. So it may be possible that there were certain greater enhanced mechanisms involved in the HR seed compared with HS seed, which delayed the germination/emergence of the seed to some degree. Irrespective of herbicide resistance, the results show that populations of *L. rigidum* may vary in emergence patterns and as a result WEEDEM should probably be calibrated to local populations, in this case from the Liverpool Plains. Vila-Aiub *et al.* (2005) observed similar emergence results with herbicide-resistant and susceptible *L. rigidum* phenotypes. They found that the susceptible phenotype emerged more from deep burial than two herbicide-resistant phenotypes.

Use of WEEDEM in cultivated conditions

The WEEDEM model takes into account factors such as last year's crop, the seeding system, soil type and soil water content as well as daily rainfall and minimum and maximum air temperatures. It converts the input data into data that correlates with *L. rigidum* emergence such as soil temperature, soil moisture and soil water potential. The WEEDEM model does not involve inputs about the type of tillage involved before the crop is sown. Field preparation before sowing of the seed involved cultivation which possibly was responsible for the delay in germination of the greater part of the seed until after the first week post sowing. Burial of seed to at least 5 cm depth also probably delayed emergence of *L. rigidum* seeds compared with seed on the soil surface. Gramshaw and Stern (1977) indicated that total seedling emergence

and the rate of this process are determined by the location of the seeds within the soil profile.

The emergence pattern predicted by this model is based on a zero-till tillage system where most of the fresh seed from the previous year lies on the surface (0-2 cm) and germinates quickly as soon as it experiences ideal climatic conditions. Most of the emergence in the field in this trial occurred in the 2nd and 3rd weeks which can be correlated with the predicted emergences by WEEDEM in the 1st and 2nd weeks (Figures 6.10 and 6.11). It is likely that if the site was not cultivated or seeds buried in this field trial, the pattern of emergence may have been better in line with that produced by the WEEDEM model.

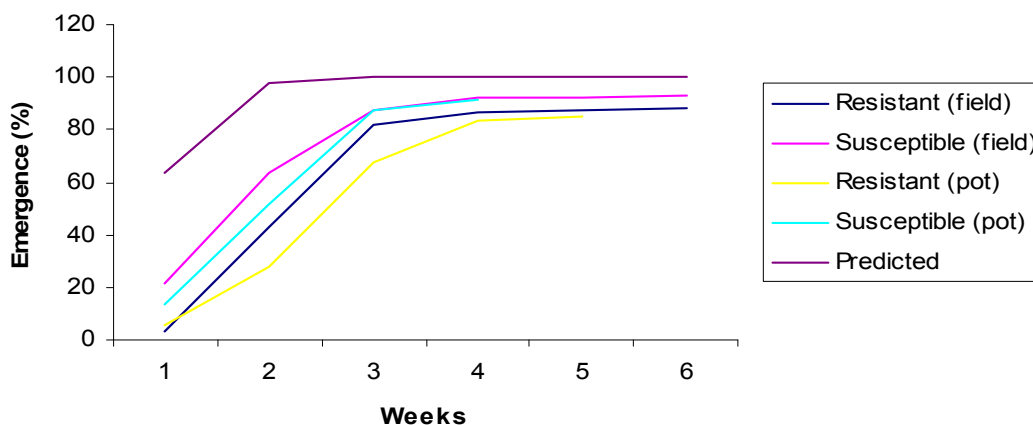


Figure 6.10 Cumulative HS and HR *L. rigidum* emergence in field and pot and predicted by WEEDEM in 2005 at the Laureldale research station and UNE campus.

About 90% of emergences predicted by WEEDEM were in the first 2 weeks. The possible reason for the difference may be related again to the depth of sowing of *L. rigidum* seed as the seeds in pots emerged in higher numbers in the 2nd week. Qunitanilla *et al.* (2000) found that the seeds of *L. rigidum* buried at various depths in the soil profile have different emergence patterns. Total seedling emergence for seeds buried at greater depths is likely to be much lower, reducing the rates of population growth. Deep burial may result in an extended emergence period and longer seed survival though burial of *L. rigidum* seed up to 10 cm deep either at Tamworth in the field or in pots at Armidale did not extend seed survival beyond 16 months (Chapter 5).

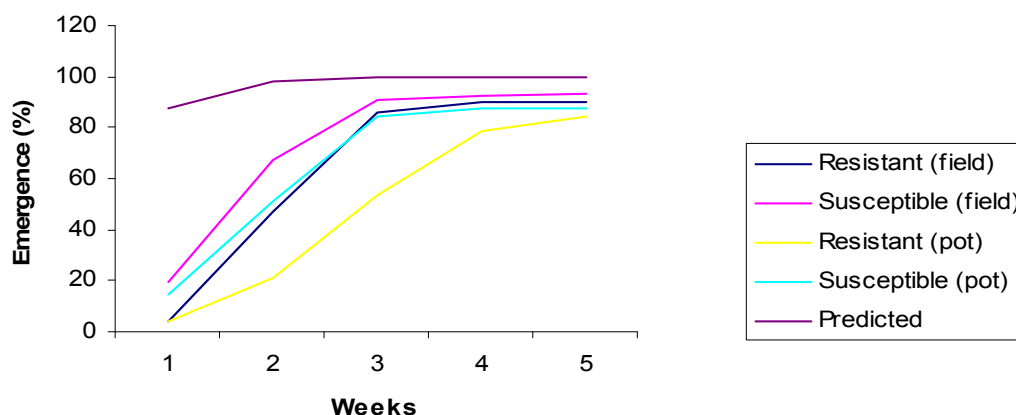


Figure 6.11 Cumulative HS and HR *L. rigidum* emergence in field and pot and predicted by WEEDM in 2006 at the Laureldale research station and UNE campus.

It is important to take into account the age of seeds before making any predictions either in the field or in pot studies, as age and dormancy characteristics of the seed may affect the prediction of emergence. The seed used in the field and pot experiments was collected from the previous season in the case of HR seed and purchased from a seed merchant in the case of HS seed and stored at 4°C. The emergence predicted by WEEDM is based on the previous year's seed shed in the field. But there may be some differences in the values predicted in the field compared with this trial, since the seed was incorporated into the field and pots just before initiation of the experiment. Under field conditions, the seed is likely to remain on the surface or in the upper part of the soil. There is some portion of seed which will percolate deep in the soil through cracks or is moved by insects or rodents or is dispersed by the action of wind and rainfall. Nevertheless, the emergence patterns may change in the event of cultivations performed immediately after seed shed in one year or before the start of the next growing season.

6.5. Conclusions

- One population of seeds had the ability to emerge more quickly than the other.
- The rate of change in emergence of *L. rigidum* seeds largely depends on moisture levels of the soil.

- The WEEDEM model did not provide accurate *L. rigidum* emergence values under cultivated conditions where the seed is placed at depth. Under cultivated conditions, where the placement of seed is between 0-5 cm depths, the majority of *L. rigidum* emergence occurred 2-3 weeks after sowing.
- For management, assuming that the model predicts accurate emergences under no-till and cultivated situations, grain growers would have greater flexibility in planning the management practices to control *L. rigidum*. For example, prediction of emergence at the time of crop sowing may allow the sowing operation to be delayed to make use of non selective herbicides or cultivation or ploughing to kill emerging weed seedlings. If *L. rigidum* is predicted to emerge in high numbers, then alternative competitive crops may be able to be introduced based on these predictions.
- The HS and HR seeds varied in emergence patterns and therefore WEEDEM should be calibrated according to local populations.

Chapter 7. Management

7.1. Introduction

In current agricultural systems zero tillage is often considered as the most profitable, consistent and environmentally friendly cropping practice. However, long term zero tillage systems, specifically in Australia, have often compelled farmers to use the same herbicides year after year with few possible alternatives. Continuous implementation of this farming type, however, has induced a number of problems. With little disturbance of soil, the development of resistance as a consequence of continuous use of herbicides was inevitable.

Under reduced tillage systems, shed seeds remain close to the soil surface (chapter 4) where there is a high likelihood of germination and emergence (Cardina *et al.* 1991, Froud-Williams 1988, Spandl *et al.* 1999). Conservation tillage systems may also move weed community composition towards particular problem weeds, e.g. grasses and vegetatively reproducing species (Arshad *et al.* 1995, Young *et al.* 1996, Zanin *et al.* 1997). A decline in overall crop returns and ecological pressure against the systematic use of herbicides are causing farmers to consider alternative approaches to weed control (Forcella *et al.* 1993a, Swanton and Weise 1991, Thornton *et al.* 1990).

Seed banks are the main source of future weed infestations and when they are removed from or reduced in the soil, plant colonization and soil coverage takes longer (Marks and Mohler 1985a). Depletion of seed banks through the use of modified tillage practices may facilitate reduced reliance on herbicides and associated problems of resistant weeds. Diversity of seed banks has been found to increase from use of the mouldboard plough, to the disk plough, to the chisel plough and finally to no-tillage, which has the most diverse seed banks (Feldman *et al.* 1997). Likewise, Blackshaw *et al.* (1994) reported that weed densities were greater in zero-tillage plots than in either minimum-tillage or conventional tillage plots. Other alternative management practices include crop rotations and burning. All may lead to decreased seed banks. However, tillage systems appear to influence weed seed bank size, composition and vertical distribution more than modified crop rotation. Altering tillage practices can change the composition, vertical distribution, and density of weed seedbanks in agricultural

soils (Barberi and Cascio 2001, Buhler 1997). Wilson (1988) reported that cultivation can deplete the active seedbank by inducing weed seed germination.

Several studies have documented that conservation-tillage increased the density of perennial weeds, some annual grasses, and volunteer crops (Derksen *et al.* 1993, Froud-Williams 1988). Whereas, ploughing may reduce total weed seed population densities in the soil and grass weed seed density more than that of broad leaf weeds (Burnside *et al.* 1986).

Annual ryegrass (*Lolium rigidum*) is one of the most important weeds in the southern Australian cropping region (Western Australia, South Australia, Victoria, and New South Wales) (Pannell *et al.* 2004). The over reliance on herbicides has resulted in the evolution of herbicide resistance in many *L. rigidum* populations. *Lolium rigidum* also has the greatest number of herbicide resistant populations of all weeds in Australia (Gill 1995, Llewellyn and Powles 2001).

Summer weeds are the main ones at risk of acquiring herbicide resistance in central Queensland (Walker *et al.* 2002, Walker *et al.* 2004), whereas a mixture of summer and winter weeds (e.g. *L. rigidum*, *Avena* spp., *Fallopia convolvulus*, *Sonchus oleraceus*, *Phalaris paradoxa* and *Hibiscus trionum*) are at risk in southern Queensland and northern New South Wales. Due to the increasing resistance threat by these weeds to one or more herbicides, there exists a need to examine management practices such as tillage and burning of residues to control these weeds. Two experiments (Armidale and Tamworth) were used to examine the value of tillage practices and stubble burning on emergence and the soil seedbank of *L. rigidum*. Another experiment at Armidale examined the value of tillage practices and stubble burning on other prominent weeds from the northern grain region. These weeds included *Polygonum aviculare*, *Phalaris paradoxa*, *Avena fatua*, *Hibiscus trionum*, *Portulaca oleracea* and *Lamium amplexicaule*. While certain practices may prove useful in controlling *L. rigidum*, we need to ensure that such practices do not promote other weed species currently in the cropping system.

7.2. Methods

***Lolium rigidum* experiment (Armidale)**

Site

The field experiment was conducted at the University of New England's Laureldale Research Station, Armidale, NSW, Australia (30°30'S, 151°40'E) at approximately 1000 m above sea level. The soil was medium heavy clay chocolate basalt soil (0-10 cm depth, pH 6.4, and 2.8% organic matter) and the trial ran in 2004 and 2005. The field used for the trial was under no tillage and had not been cropped previously for 3 years.

Treatments

The treatments were;

- no tillage (NT);
- chisel ploughing (CP);
- mould board ploughing (MBP);
- wheat straw burning with no tillage (SBNT); and
- wheat straw burning with chisel ploughing (SBC)

Design

The trial comprised five treatments replicated four times in a randomized complete block design.

Initial viability test

The procedure for this test is similar to the one performed in Chapter 5.

Field operation

The trial consisted of 20 main plots each of 1.4 x 6.6 m with 2 m buffers between them. Commercially purchased *L. rigidum* seed was broadcast on the soil surface at a rate of 1000 seeds m⁻², 2 days before tillage operations were applied on 11 August, 2004. In 2004, due to the absence of straw in the field, SBC and SBNT were treated as no tillage plots as no burning or tillage was carried out in these two treatments. MBP (three furrows) involved inverting the soil down to 25-30 cm followed by light CP to break the large clods and level the soil surface. Chisel plough (2.18 m wide)

comprised two runs back and forth to a depth of 15 cm. The wheat crop cv. Janz was sown in August in both years 1 day after the tillage treatments at 100 kg ha⁻¹ using a cone seeder with 7 rows per plot and a spacing of 20 cm between rows. The crop was fertilized with broadcast urea at the rate of 30 kg N ha⁻¹. In 2005, 1 month prior to applying the tillage treatments, the straw burn treatment plots were burned uniformly with the assistance of a kerosene flame burner (Figure 7.1).



Figure 7.1 Burning of wheat stubble in 2005 at Armidale

Plots were then later tilled on 10 August, 2005 and sown to wheat as in 2004 (Figure 7.2). Rainfall and temperature data recorded in 2004 and 2005 at the site are shown in Figures 7.3 and 7.4.



Figure 7.2 Wheat sown after tillage in 2004 at Armidale

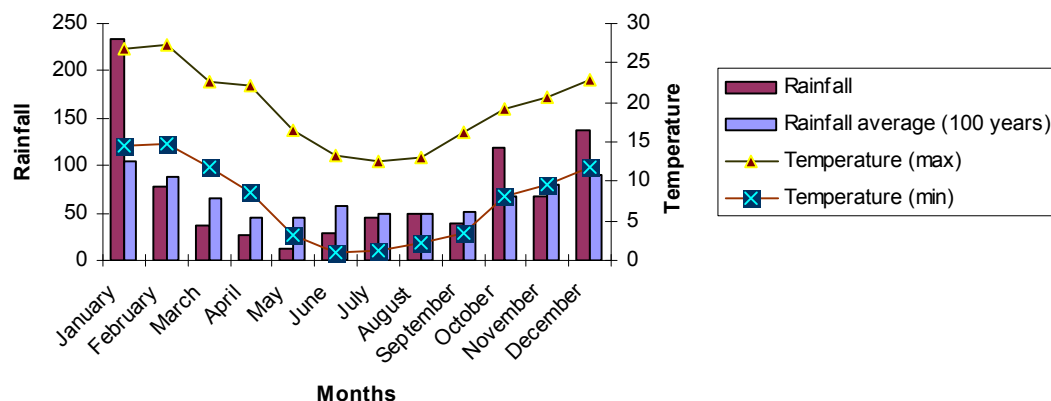


Figure 7.3 Total monthly rainfall (mm) and mean monthly temperature (max and min °C) during 2004 and average rainfall of 100 years at Laureldale Research Station, Armidale.

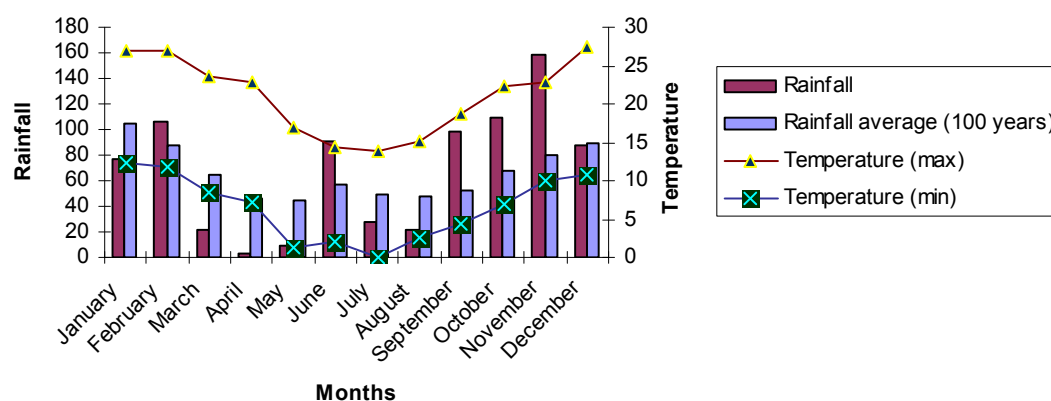


Figure 7.4 Total monthly rainfall (mm) and mean monthly temperature (max and min °C) during 2005 and average rainfall of 100 years at Laureldale Research Station, Armidale.

Data collection

Weed density was counted in four quadrats per plot using a 30 x 30 cm steel frame at 30, 60 and 120 days after sowing (DAS) of the wheat crop in 2004 and 2005. Crop density was also counted in a similar way at 30 and 60 DAS. Sampling of treatment plots to obtain the initial seedbank numbers of *L. rigidum* in each plot was planned in 2005 before applying burning treatments. However, due to persisting rains for 30-45 days during this period, sampling could not be performed due to saturated soil conditions. In order to attain an idea of seed numbers, above ground *L. rigidum* numbers were counted 7 days before tillage operations were performed in 2005. *Lolium rigidum* heads were cut and allowed to fall in each plot before grain harvest in 2004 and 2005. Wheat grain yield of each whole plot was recorded at harvest in January 2005 and 2006. Ten heads of wheat were randomly cut; total grains counted

and averaged over ten heads to assess grains head⁻¹. Two hundred seeds were counted from the harvested grains; were weighed and expressed as 1000 grain weight. The field was left undisturbed between harvest and the following cropping season.

Seedbank analysis

Before the initiation of the experiment, seedbank analysis was not performed for any latent seedbank, as the field had no previous history of *L. rigidum*. In November, 2004 and 2005, the seedbank was measured before the *L. rigidum* plants flowered and in 2005 the plots were again sampled after the *L. rigidum* seeds were shed but before harvest. Keeping in mind the size of the plots, 10 soil samples were collected randomly from each individual plot using steel cores of 5 cm diameter and 10 cm depth. The samples were bulked and stored at 4°C for 4 months. The thoroughly mixed samples were then spread to a depth of approximately 4 cm in 36 x 29 cm plastic trays with holes in the base for drainage. The trays were placed randomly in a polyhouse with a temperature range of 15-35°C and watered to field capacity. Weeds were identified, counted and uprooted as they emerged in accordance with the procedure described by Forcella *et al.* (2003). After 4 weeks, soil in the trays was allowed to air dry for 1 week, soil was inverted and mixed thoroughly and then placed back in trays for another week of watering and counting of any emerging weeds.

Data analysis

The data were fitted with a linear model in R 2.3.0 (R Development Core Team 2006) and presented with a linear regression (Equation 3.2) and 95% confidence limits.

Treatment effects were evaluated at individual time points for weed density and tiller density of wheat using the ANOVA function. Diagnostic plots were used to check the homogeneity of variance and normality of the data for each response variable and no transformations were necessary. The *P* values for ANOVA are presented in the results section to indicate the level of significance. Data for the weed density 7 days before tillage, seedbanks, grain yield, grains per head and thousand grain weights were compared using means and standard errors and represented as standard error bar plots.

Other species experiment (Armidale)

This experiment which looked at other important weeds from the northern grain region was conducted in an area adjacent to the annual ryegrass experiment and utilised weed seedbanks already in the soil. The methods and timing of the trial were otherwise the same as that for annual ryegrass experiment, except that in 2004, before applying the tillage treatments, soil sampling was conducted to estimate the initial seed bank of the various weed species in individual plots. The sampling protocol was the same as that previously described. Data analysis was performed in the similar way to that of annual ryegrass experiment at Armidale for different weeds.

***Lolium rigidum* experiment (Tamworth)**

Site

The New South Wales Department of Primary Industries Tamworth Agricultural Institute at Calala is situated approximately 100 km south of Armidale in the New England region of New South Wales about 10 km south east of the city of Tamworth at 31° 08' S and 150° 59' E at an elevation of 450 metres above sea level. Tamworth is located on the edge of the Liverpool Plains and at the eastern edge of the northern grain region of NSW. The soil of the experimental field was dark reddish brown dry light clay (0-10 cm, pH 6.5, organic matter 3.0%). Calala receives an annual rainfall of 675 mm with almost 65 % falling in the 6 months from October to March. The trial ran over 2005 and 2006 and the field used for the trial had been cropped previously with wheat under a no tillage system.

Treatments

The treatments were;

- no tillage (NT);
- chisel ploughing (CP);
- mould board ploughing (MBP);
- wheat straw burning with no tillage (SBNT);
- wheat straw burning with chisel ploughing (SBC); and
- diclofop-methyl (Hoegrass ®) application on a NT plot.

Design

The trial comprised six treatments replicated four times in a randomized complete block design.

Initial viability test

The procedure for this test is similar to the one performed in Chapter 4.

Field operation

The treatments comprised 24 main plots each of 3.3 x 10 m with 2 m buffers between them. Commercially purchased *Lolium rigidum* seed used in the Armidale experiment was broadcast by hand on the soil surface at a rate of 1000 seeds m⁻² 2 days before burning was initiated in required plots. In 2005, burning was planned 1 month prior to application of tillage treatments but rainfall persisted during June and July and kept the field wet. Therefore sowing was delayed for 2 months and burning was initiated 3 months prior to applying the tillage treatments. The straw was burnt uniformly with the assistance of a kerosene flame burner. Three months after burning, tillage treatments were applied in the respective plots. Mouldboard ploughing involved, inverting the soil down to 25-30 cm followed by light CP to break the large clods and level the soil surface (Figure 7.5). Chisel ploughing comprised two runs back and forth to a depth of 15 cm (Figure 7.6). The same equipment was used as in the Armidale experiment. One day after performing the tillage treatments the wheat crop cv. Lang was sown on 27 July, 2005 at 80 kg ha⁻¹, using a cone seeder with a spacing of 10 cm between the rows (Figure 7.7). The crop was fertilized with urea at the rate of 100 kg of N ha⁻¹ broadcast by hand and single super phosphate was applied to give 5 kg ha⁻¹ S and 4 kg ha⁻¹ P with the wheat sowing equipment.



Figure 7.5 and 7.6 Mouldboard Plough and Chisel Plough treatments plots in 2005 at Tamworth

Adjoining areas of experimental field were sprayed with various herbicides to keep them weed free. On 19 August 2005 (3 weeks after crop was sown) the herbicide plots were sprayed with diclofop- methyl at 280 g ha⁻¹. All plots were sprayed with flamprop-M methyl on 24 August 2005 at 260 g ha⁻¹ 5 to control *Avena* spp., picloram at 26 g ha⁻¹ + MCPA at 420 g ha⁻¹ on 26 August 2005 to control *Fallopia convolvulus* and again with fluroxypyr at 500 g ha⁻¹ on 3 November 2005 for *F. convolvulus*.



Figure 7.7 Wheat sowing with seed drill in 2005 at Tamworth

Data collection

Lolium rigidum weed density and crop tiller density was counted in six quadrats per plot using a 30 x 30 cm steel frame at 30, 60 and 120 days after sowing (DAS) of the wheat crop in 2005. *Lolium rigidum* heads were cut and allowed to fall in each plot before grain harvest in 2005. Grain yield of wheat of each whole plot was recorded at harvest 15 December 2005. The field was left undisturbed between harvest and the following cropping season. In 2006, 7 days prior to normal crop sowing time on 16 June 2006, *L. rigidum* seedlings were counted to determine the resultant densities from the one year of treatments. The wheat crop was not sown in 2006 so as to see the effect of glyphosate on residual seedbank numbers after one year of tillage treatments. The plots were all sprayed with glyphosate at 900 g ha⁻¹ for knockdown of all weed flora and one final count of *L. rigidum* was taken in spring on 16 October 2006 to record numbers of newly emerged *L. rigidum* plants. Rainfall and temperature data recorded in 2005 and 2006 at the site are shown in Figure 7.8 and 7.9.

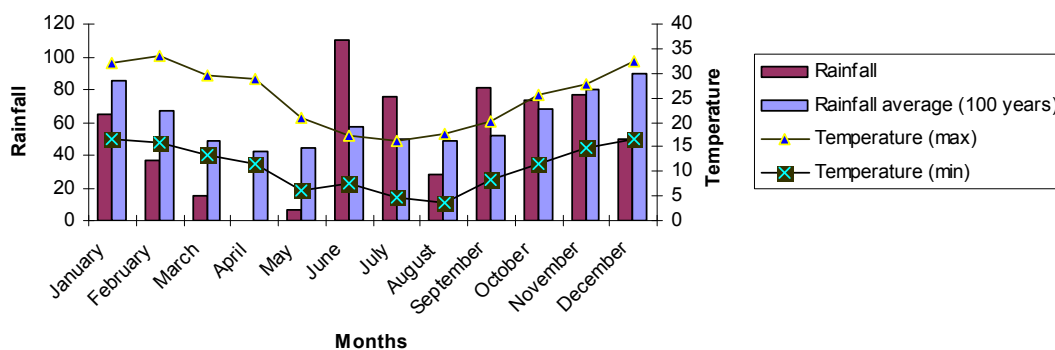


Figure 7.8 Total monthly rainfall (mm) and mean monthly temperature (max and min °C) during 2005 and average rainfall of 100 years at Tamworth Agricultural Institute.

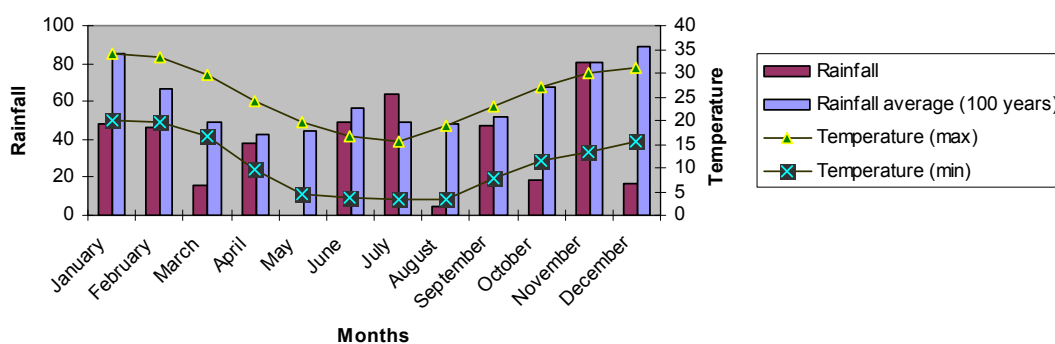


Figure 7.9 Total monthly rainfall (mm) and mean monthly temperature (max and min °C) during 2006 and average rainfall of 100 years at Tamworth Agricultural Institute.

Seedbank analysis

On 17 October 2006 seedbanks of *L. rigidum* were measured in each plot by taking 20 cores of 5 cm diameter from 10 cm depth. Seed germination procedure was similar to the annual ryegrass experiment at Armidale.

Data analysis

The data were fitted with a linear model in R 2.3.0 (R Development Core Team 2006) and presented with a linear regression (Equation 3.2) and 95% confidence limits.

Treatment effects were evaluated at individual time points for weed density and tiller density of wheat using the ANOVA function. Diagnostic plots were used to check the homogeneity of variance and normality of the data for each response variable and no transformations were necessary. The *P* values for ANOVA are presented in the results section to indicate the level of significance. Data for the weed density 7 days before

tillage, seed banks and grain yield were compared using means and standard errors and represented as standard error bar plots.

7.3. Results

***Lolium rigidum* experiment (Armidale)**

The results from the germination and dormancy experiment initiated before the start of the experiment indicated that out of 50 glyphosate resistant *L. rigidum* seeds, 85 % seeds were germinable, 10 % seeds were viable but dormant and remaining 5 % were dead.

The overall ANOVA for the experiment for the first 4 months after sowing over 2004 and 2005 indicated that the three way interaction between days after sowing x treatment x year ($P= 0.756$) was not significant. All the other two way interactions and the main terms were significant ($P\leq 0.01$). Weed densities of *L. rigidum* over the 4 months sampling period are presented in Figure 7.10.

Lolium rigidum density in 2004 and 2005

Lolium rigidum plant density across all the treatments declined over the sampling period of 30 -120 DAS in 2004 (Figure 7.10). At all the sampling dates, (based on the mean values) the highest *L. rigidum* density was observed in all the NT plots and the minimum in MBP plots followed by CP. After the last sampling, the largest *L. rigidum* reduction over the sampling period was observed in CP (62%) followed by MBP (49%). In general, the rate of reduction of *L. rigidum* density was highest with CP ($b= -2.18$) and least in NT plots. Rate of change of *L. rigidum* density over time was not significant for MBP ($P= 0.124$), SBC and SBNT plots.

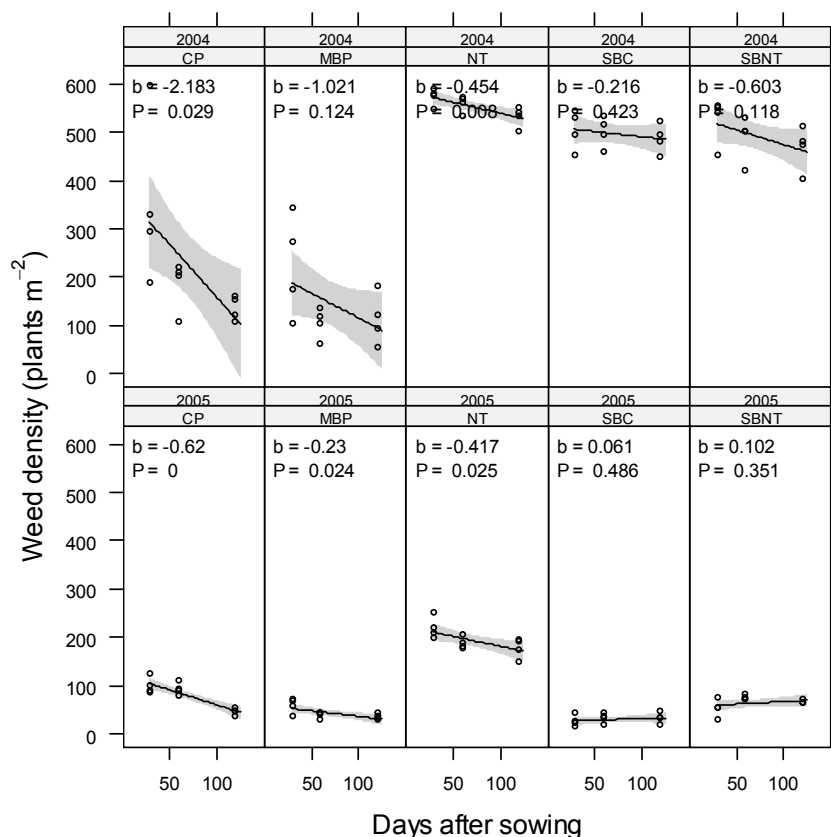


Figure 7.10 *L. rigidum* density at 30, 60 and 120 DAS (days after sowing) in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

In 2005, *L. rigidum* seedlings emerged early because of early rain (Figure 7.4). Seven days before tillage and sowing, *L. rigidum* density of emerged seedlings from the previous year's seedbank was lowest in the MBP (257 m⁻²) followed by the NT (324 m⁻²) and highest in the previously CP and recently burnt plots (SBC and SBNT) (Figure 7.11). After cultivation and sowing, numbers of *L. rigidum* plants fell rapidly in all the treatments (Figure 7.10) though least in the NT plots. Most of these later plants were freshly germinated, though there were small proportions that survived the tillage and sowing operations.

At 30 DAS, density of *L. rigidum* was least in the SBC followed by SBNT and the MBP treatments and highest in the NT. At 60 DAS, the population of *L. rigidum* decreased in all the plots except the straw burning treatments where there was an increase in the emerged populations (Figure 7.10). Straw burning cultivation still had the lowest numbers followed by MBP. At 120 DAS the number of *L. rigidum*

seedlings remained more or less the same in the straw burnt plot, however, there was a decrease in the density in the other plots. After the last sampling, the largest *L. rigidum* reduction over the sampling period was observed in CP (54%) and MBP (40%). Overall, the rate of reduction in the density of *L. rigidum* over time was significant and greatest in CP ($b = -0.62$) followed by NT ($b = -0.41$) and MBP ($b = -0.23$). The rate of change was significant in all except SBC and SBNT plots.

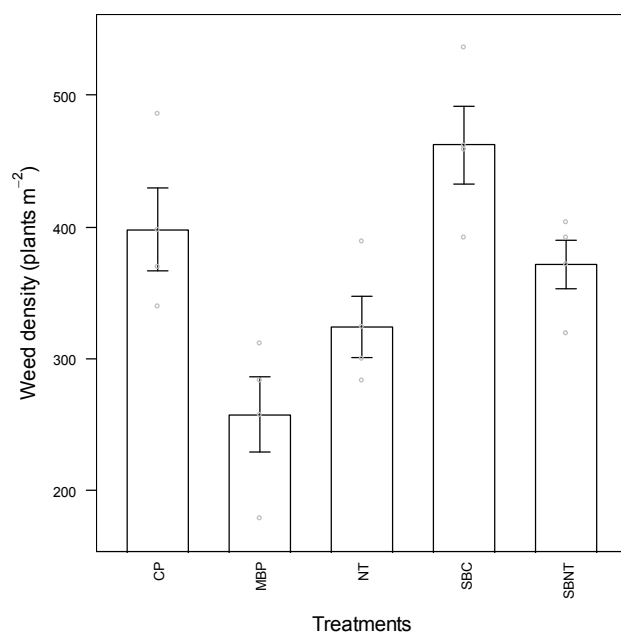


Figure 7.11 *Lolium rigidum* weed density 7 days before tillage treatments in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Seedbank levels

No *L. rigidum* seed was found in the soil samples from 2004, nor before flowering of *L. rigidum* plants in 2005. The second sampling in 2005 before the harvest of wheat when ripened ryegrass seeds were allowed to fall in the respective plots showed that the SBC treatment had limited the *L. rigidum* seedbank the most to less than 1500 seeds m⁻² followed by CP and MBP (both about 2000 m⁻²). Straw burning no tillage treatments had maximum seedbank numbers over 5000 m⁻² followed by NT with seedbanks greater than 3000 m⁻² (Figure 7.12).

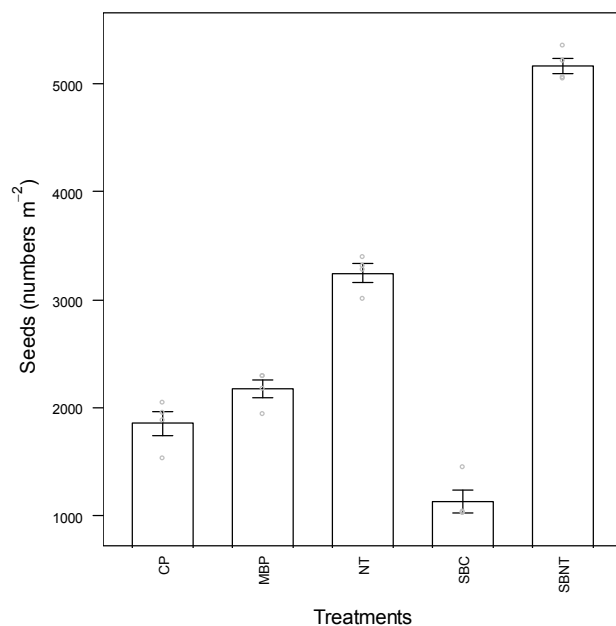


Figure 7.12 *Lolium rigidum* seedbank data after harvest in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Crop tiller density in 2004 and 2005

Tiller densities of the wheat crop 30 and 60 DAS are presented in Figure 7.13. The ANOVA for the experiment indicated that except the treatments main term ($P=0.811$) all the other three way, two way interactions and the main terms days after sowing and year were significant ($P \leq 0.01$).

Tiller numbers across all the treatments increased over the sampling period in 2004 (Figure 7.13). The highest tiller density was observed in CP and SBNT at 30 DAS, and the lowest in MBP followed by NT (based on the mean values). At 60 DAS, the tiller population of the crop increased strongly in all the treatments with the highest in NT followed by MBP and the lowest density in CP. The rate of increase of tiller density was highest with MBP ($b=14.9$) followed by NT ($b=13.7$), and least in CP plots. Rate of change of crop density over time was highly significant for all the treatment plots in 2004.

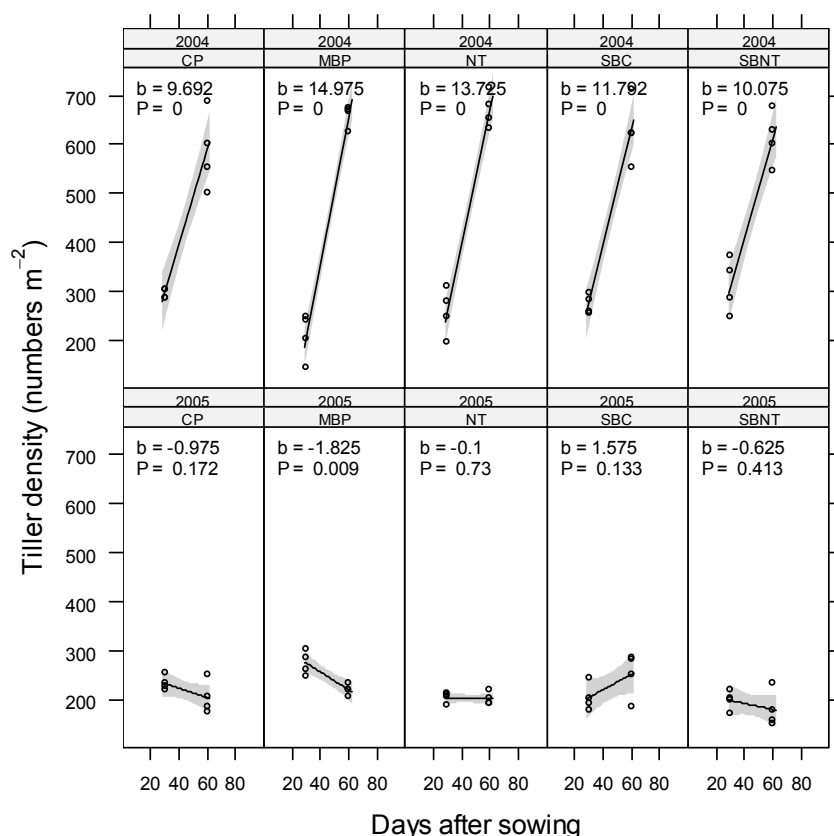


Figure 7.13 Tiller density of wheat at 30 and 60 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

In 2005, at 30 DAS, crop density was least in SBNT followed by SBC and NT and highest in MBP (Figure 7.13). At 60 DAS, the population of the wheat crop decreased in all the treatments except SBC ($b = 1.57$) where there was an increase in the emerged wheat crop density. The lowest numbers recorded were in SBNT followed by NT and CP. Excessive rainfall was associated with higher densities of *L. rigidum* and other mixed weed flora. Overall, the maximum rate of decrease in the density of the wheat crop in 2005 among the treatments over time was significant and greatest in MBP ($b = -1.82$) followed by CP ($b = -0.97$), which was not significant. The rate of increase or reduction was not significant in any of the other treatments ($P \geq 0.133$).

Wheat grain yield in 2004 and 2005

In 2004 (Figure 7.14), the grain yield of all treatments was above 5300 kg ha⁻¹. It was highest in one of the no-till treatments (NT) at 6126 kg ha⁻¹ and lowest in MBP at 5367 kg ha⁻¹. CP was similar in yield to the no-till treatments. In 2005, yields were

highest and similar in the SBC, CP and MBP treatments. In contrast, the SBNT and NT treatments yielded very poorly. Overall, the yields in 2005 were far less than those in 2004.

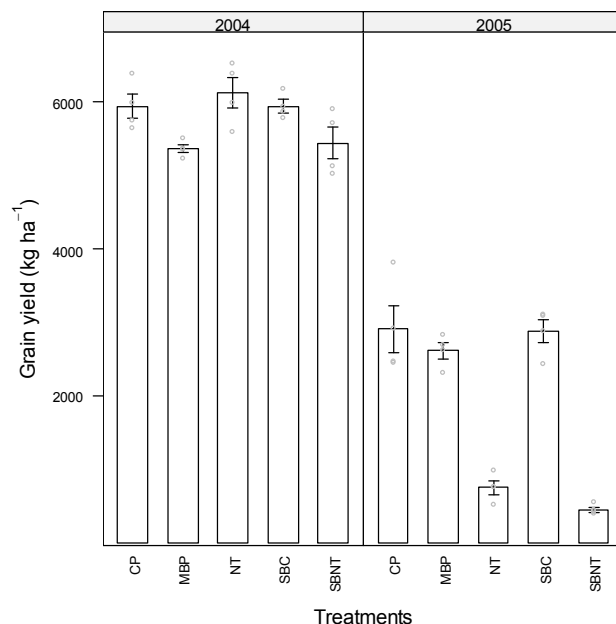


Figure 7.14 Grain yield (kg ha⁻¹) in 2004 and 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Grains per head

In 2004, NT had the highest number of grains head⁻¹ followed by the MBP and SBC and the lowest grain numbers were recorded with SBNT (Figure 7.15). No tillage had significantly higher grains head⁻¹ compared with CP and SBNT. However, in the following year the trend was different with the MBP and SBC treatments experiencing the maximum number of grains head⁻¹ whilst the lowest were with SBNT followed by NT similar to the results for grain yield. Straw burning cultivation, MBP and CP had significantly higher grains head⁻¹ than NT and SBNT. The SBNT treatment in 2005 had approximately 50% of the grains head⁻¹ compared with the same treatment in 2004. The number of grains head⁻¹ showed a similar pattern to that of grain yield across treatments.

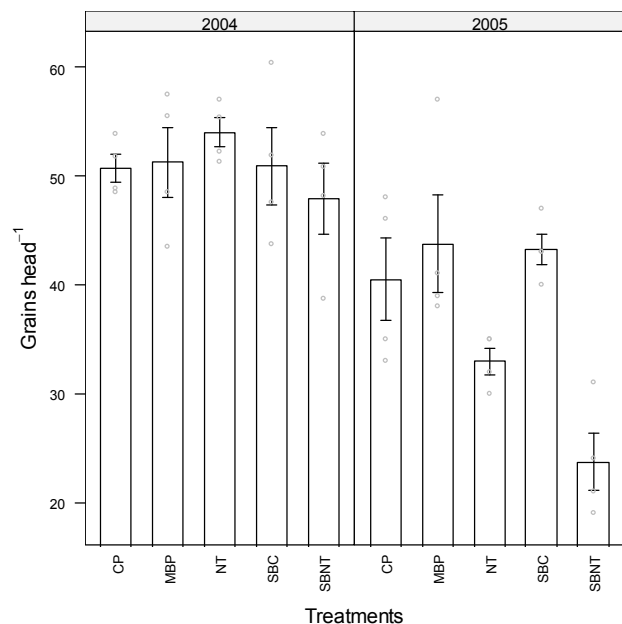


Figure 7.15 Grains head⁻¹ of wheat at harvest in 2004 and 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Thousand grain weight

In 2004, the highest average grain weight was observed with the three treatments considered as under no tillage (NT, SBNT and SBC).

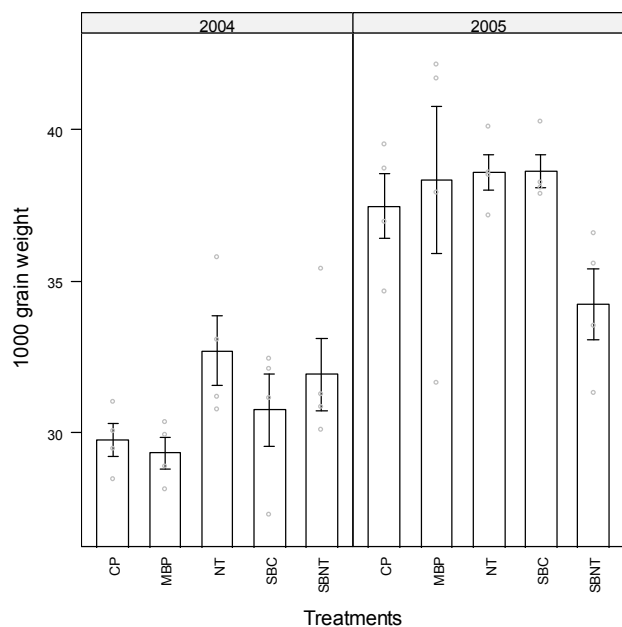


Figure 7.16 Thousand grain weight (grams) of wheat at harvest in 2004 and 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

The lowest was in MBP and CP. In 2005, the greatest grain weights were similar in the SBC, NT, MBP and CP treatments but lower in SBNT (Figure 7.16).

Other species experiment (Armidale)

General trends

In the second experiment at Armidale that relied on existing seedbanks of a variety of species, the tillage operations in 2004 resulted in large reductions in weed density and seed banks. There were 16 weed species recorded in total but eight (*Vicia sativa*, *Oxalis pes-caprae*, *Convolvulus erubescens*, *Cirsium vulgare*, *Sonchus oleraceus*, *Urochloa panicoides*, *Echinochloa* spp. and an unidentified broad leaf weed) of these had negligible counts and hence were discarded from the analysis. In both years the emerging weed species were similar except for *C. erubescens*, which emerged as a new weed in 2005 with low populations. Results have been presented for changes in populations of the 8 remaining species viz. *Polygonum aviculare*, *Hibiscus trionum*, *Avena fatua*, *Phalaris paradoxa*, *Melilotus indica*, *Lamium amplexicaule*, *Trifolium glomeratum* and *Portulaca oleracea*.

Polygonum aviculare density and seedbank

In 2004 *P. aviculare* plant density was generally highest in SBNT, SBC and NT at each of the three sampling dates (30-120 DAS) and lowest in MBP followed by CP (Figure 7.17). The first three of these treatments (NT, SBC and SBNT) in the first year were all under no-till management. The population in CP increased over time, whereas the populations either remained static or decreased in the other four treatments, although none of slopes was significant. The greatest rate of reduction in density was found in SBNT ($b = -0.062$) followed by the MBP treatment ($b = -0.043$).

The starting seedbank data for *P. aviculare* recorded before the treatments were imposed in 2004 were somewhat variable but not significantly different between treatment plots. Another seed count just before the *P. aviculare* plants flowered showed that seed counts were not affected by most of the tillage treatments at this stage. The greatest seed numbers of *P. aviculare* among the treatments were in the NT treatment and the lowest were in CP (Figure 7.18).

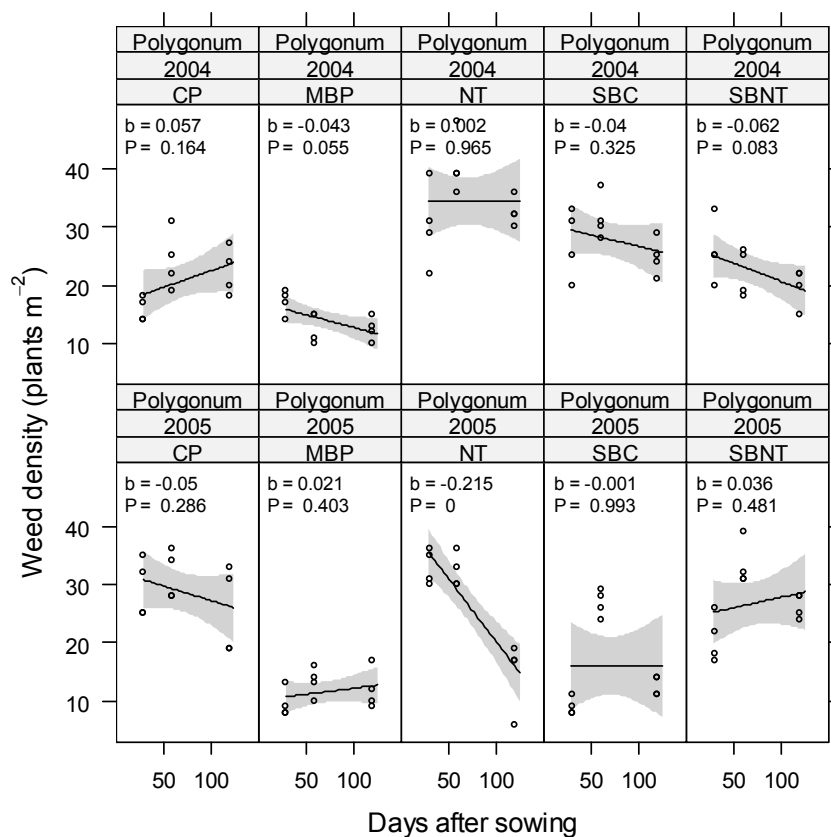


Figure 7.17 *Polygonum aviculare* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals.. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

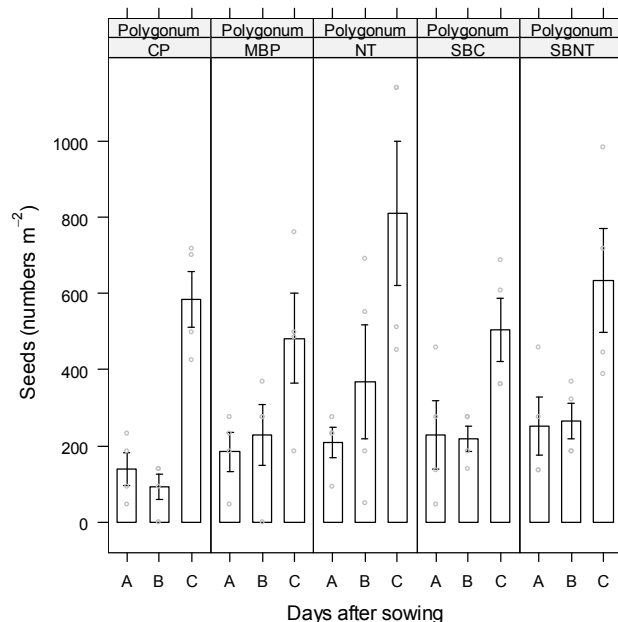


Figure 7.18 *Polygonum aviculare* seedbank data at A= before sowing and tillage (2004), B= before flowering (2004) and C= before crop harvest but after seed drop (2005). The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

In 2005, before tillage but after stubble burning, density of seedlings was significantly lower in the MBP treatment than other treatments. Straw burning cultivation was next lowest and SBNT highest (Figure 7.19). After tillage and crop sowing, numbers of *P. aviculare* plants had declined in all the treatments at 30 DAS (Figure 7.17). Most of these plants were freshly germinated with some that survived the tillage and sowing operation. Over the three samplings (30-120 DAS) in 2005, weed counts were generally lowest in the SBC and MBP treatments and highest and similar in all other treatments, similar to the early germinations before tillage. The population of *P. aviculare* slightly increased in MBP and SBNT and decreased in other treatments. The rate of reduction of density over the period was greatest in NT ($b = -0.215$) followed by CP ($b = -0.05$) (Figure 7.17). Prior to harvest of the crop but after the seeds were shed in the second year the highest seedbank was in NT treatment followed by SBNT and lowest in MBP and SBC (Figure 7.18).

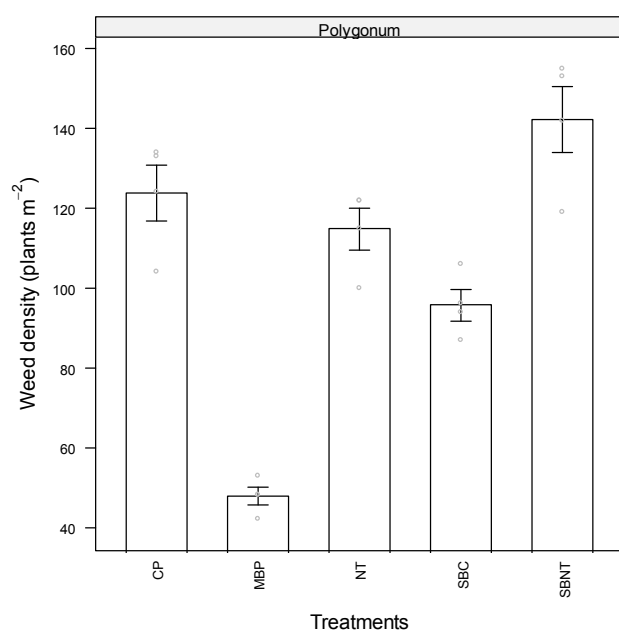


Figure 7.19 *Polygonum aviculare* weed density before sowing/tillage in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Phalaris paradoxa density and seedbank

Density of *P. paradoxa* generally increased over the three sampling periods in 2004 with nil populations at 30 DAS and subsequent low germinations at the following sampling dates (Figure 7.20). The rate of increase was greatest in CP ($b = 0.198$)

followed by MBP ($b= 0.13$) and lowest in the three NT treatments in 2004. The rate of increase was significant for all treatments except the NT treatment ($P= 0.46$).

Seedbanks of *P. paradoxa* were relatively uniform across the plots at the start of the experiment (Figure 7.21). There were large differences among the seed bank data collected before sowing and the emergence of *P. paradoxa* occurring at 30 DAS in 2004. Weed densities and seedbanks were not significantly different between the treatments at different sampling dates in 2004. The seedbanks of *P. paradoxa* were far lower at the end of the first season before flowering of the weed than at the beginning of the season (Figure 7.21).

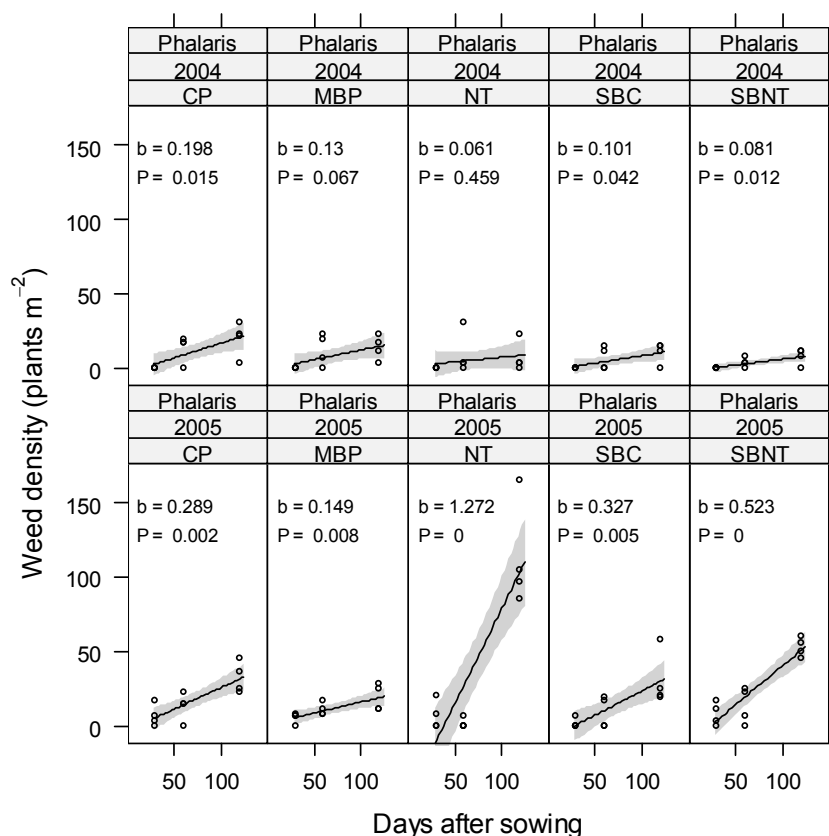


Figure 7.20 *Phalaris paradoxa* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

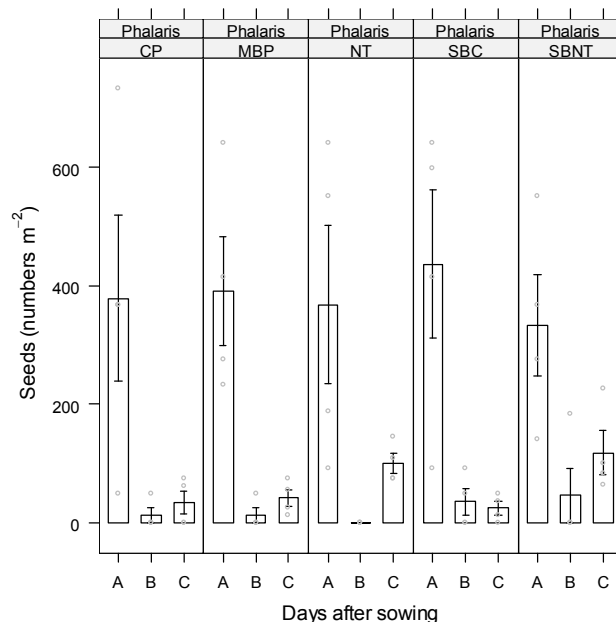


Figure 7.21 *Phalaris paradoxa* seedbank data at A= before sowing and tillage (2004), B= before flowering (2004) and C= before crop harvest but after seed drop (2005). The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Few *P. paradoxa* plants had emerged 7 DBT in 2005 with the highest numbers occurring in SBC and SBNT (Figure 7.22). This pattern corresponded to the seedbank numbers recorded before flowering in 2004. The density of *P. paradoxa* increased in all the treatments over the sampling period (30-120 DAS) (Figure 7.20). At 120 DAS, the greatest density was recorded in the NT followed by the SBNT with the lowest level in MBP plots (based on the mean values). The rate of increase in *P. paradoxa* density was greatest in NT ($b= 1.27$) followed by SBNT ($b= 0.52$) with the lowest in MBP ($b= 0.149$). The rate of increase was significant in all the treatments ($P < 0.05$) (Figure 7.20). The final seed bank recorded before the harvest of the wheat crop in 2005 had greatest numbers in SBNT followed by NT and the lowest were in SBC, CP and MBP, which were not significantly different from one another (Figure 7.21).

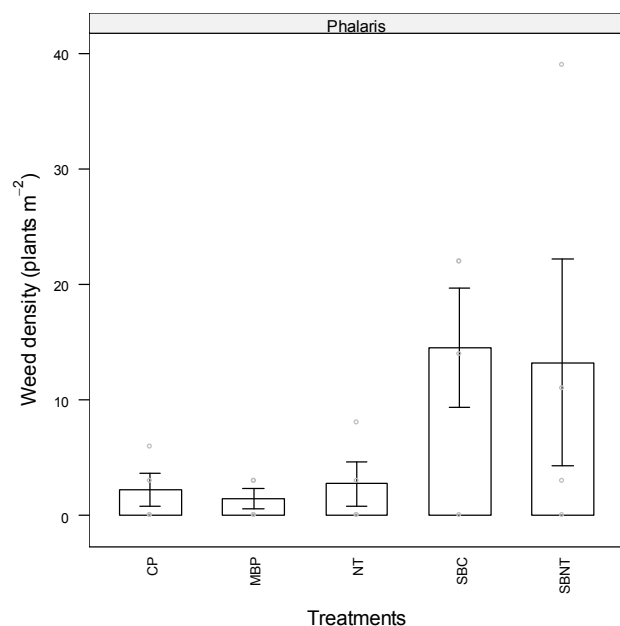


Figure 7.22 *Phalaris paradoxa* weed density before sowing/tillage in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Hibiscus trionum density and seedbank population

Density of *H. trionum* was highest in the no-till plots in 2004 and lowest in MBP and CP at all the three sampling periods (30-120 DAS) (Figure 7.23). Data from the soil samples collected before sowing/tillage in 2004 showed that the initial seedbank numbers were not significantly different between treatments (Figure 7.24). *Hibiscus trionum* density across all the treatments in 2004 increased over the sampling period. The rate of increase of weed density was greatest in two of the no-till treatments, SBC ($b= 0.27$) and SBNT ($b= 0.25$) but the rate of increase in weed density over the sampling period (Figure 7.23) was only significant in CP and MBP ($P \leq 0.013$) because of large variation in the other treatment plots. There were large reductions in the germinable seed bank of *H. trionum* from before sowing to before flowering (Figure 7.24). Chisel ploughing and SBNT had similar low numbers with nil seedbanks in the remaining treatments.

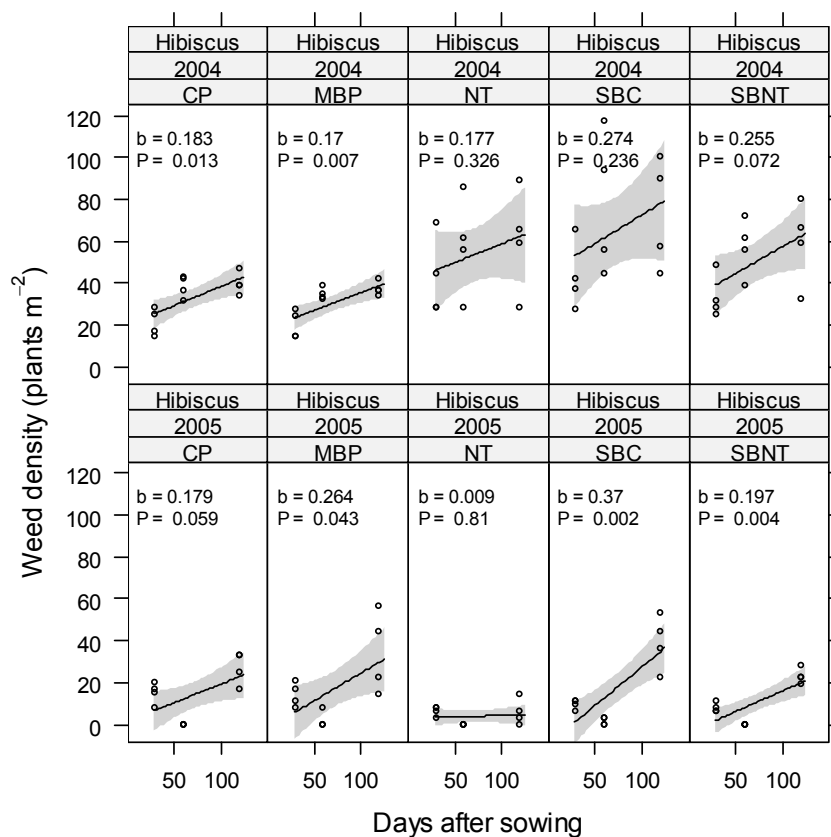


Figure 7.23 *Hibiscus trionum* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

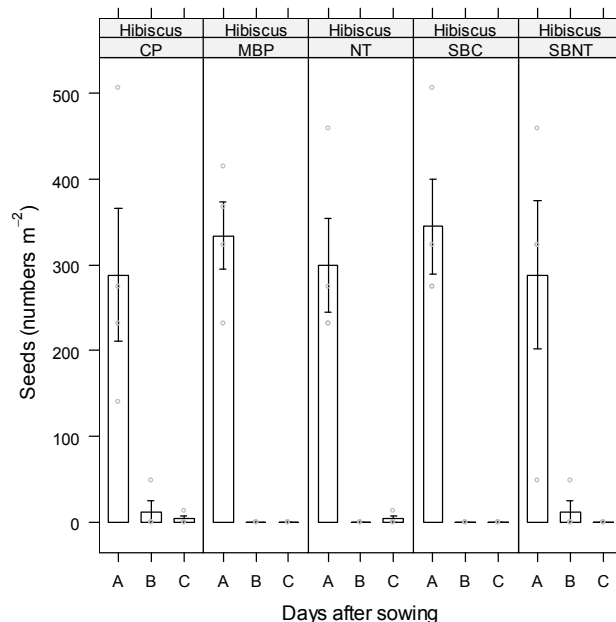


Figure 7.24 *Hibiscus trionum* seedbank data at A= before sowing and tillage (2004), B= before flowering (2004) and C= before crop harvest but after seed drop (2005). The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

In 2005, there was little emergence of *H. trionum* in all the treatments 7 DBT except in NT where there was early emergence of nearly 20 plants m^{-2} (Figure 7.25). Tillage treatments caused seedlings to emerge by 30 DAS but some of these died by 60 DAS (Figure 7.23). There was however a later germination flush at 120 DAS. *Hibiscus trionum* numbers generally increased from 30 to 120 DAS except for NT. The rate of increase was greatest in SBC ($b= 0.37$) followed by MBP ($b= 0.26$). Except for NT, the rate of increase of weed density over the sampling period was significant. Seedbank numbers at harvest in 2005 were very low in all treatments (Figure 7.24).

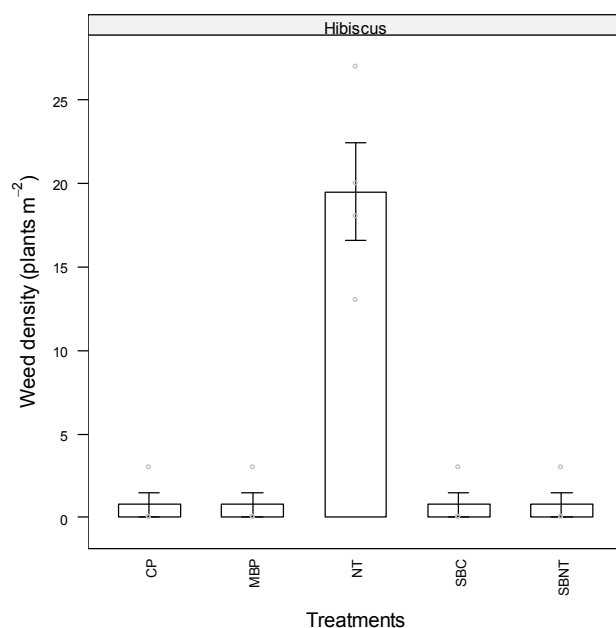


Figure 7.25 *Hibiscus trionum* weed density before sowing/tillage in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Avena fatua seed banks and weed density

There was no *A. fatua* emergence in the field in 2004 (Figure 7.26) in any of the treatments despite moderate germinable seedbanks at the start and towards the end of the season, except in the SBNT treatment (Figure 7.27). SBNT had the greatest density of *A. fatua* before application of tillage in 2005 followed by MBP whilst the lowest *A. fatua* levels were in SBC (Figure 7.28).

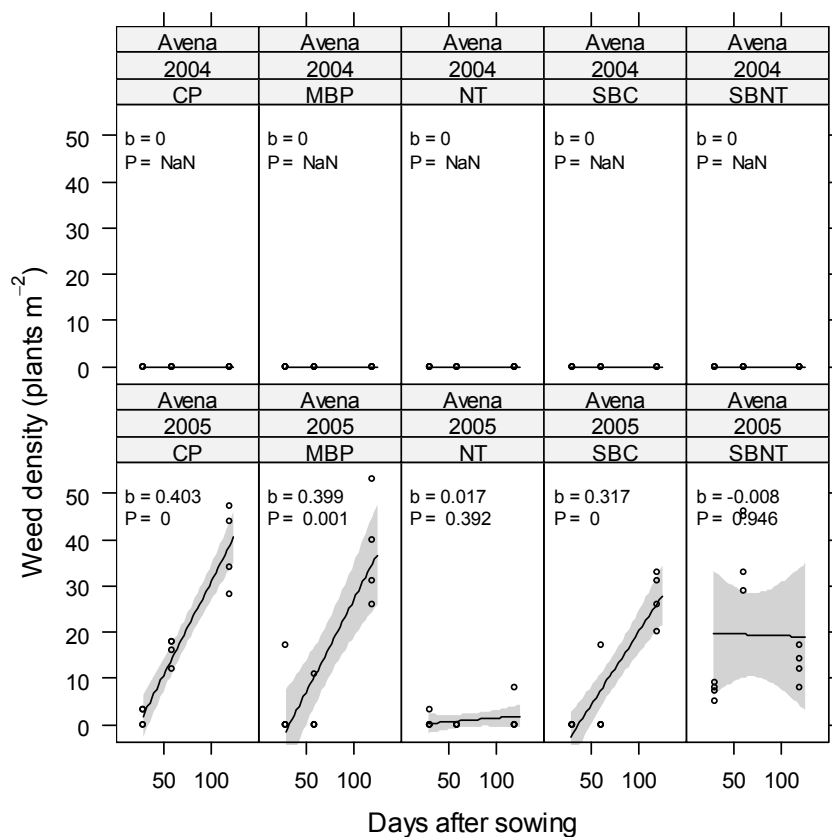


Figure 7.26 *Avena fatua* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. NaN= Not applicable number (no emergence), b = the slope and P = significance of the slope.

Emergence in 2005 was variable but the density at 30 DAS showed no significant differences between the treatments (Figure 7.26). The population of *A. fatua* increased with sampling time for all the treatments except SBNT which were variable over time increasing dramatically at 60 DAS but decreasing as equally dramatically by 120 DAS. At 120 DAS, the greatest numbers of *A. fatua* plants were recorded in CP, MBP and SBC and the lowest in NT and SBNT. The rate of increase in density was greatest in CP ($b= 0.403$) and MBP ($b= 0.39$) and lowest in NT ($b= 0.017$). The seedbank data at harvest in 2005 (Figure 7.27) are in line with the figures for weed density observed in 2005 except for SBC where there was no germinable seedbank despite relatively high seed production (Figure 7.27). It may be possible that seed of *A. fatua* from 2005 was dormant and that the seedbank measurements were from older seeds.

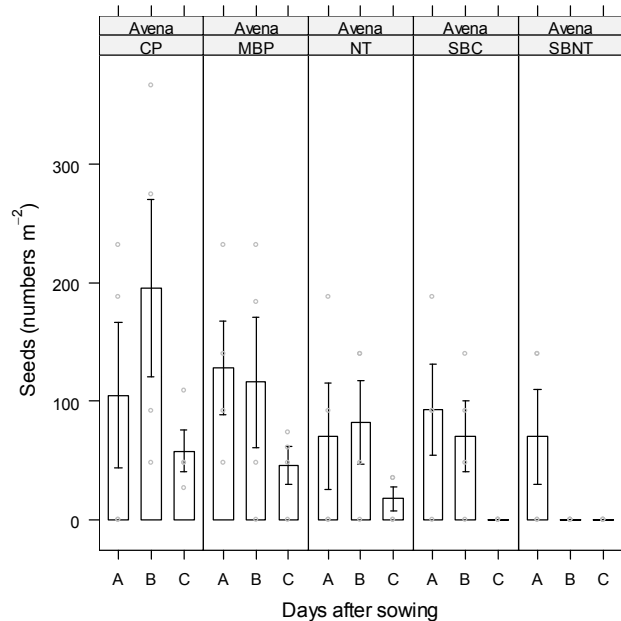


Figure 7.27 *Avena fatua* seedbank data at A= before sowing and tillage (2004), B= before flowering (2004) and C= before crop harvest but after seed drop (2005). The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

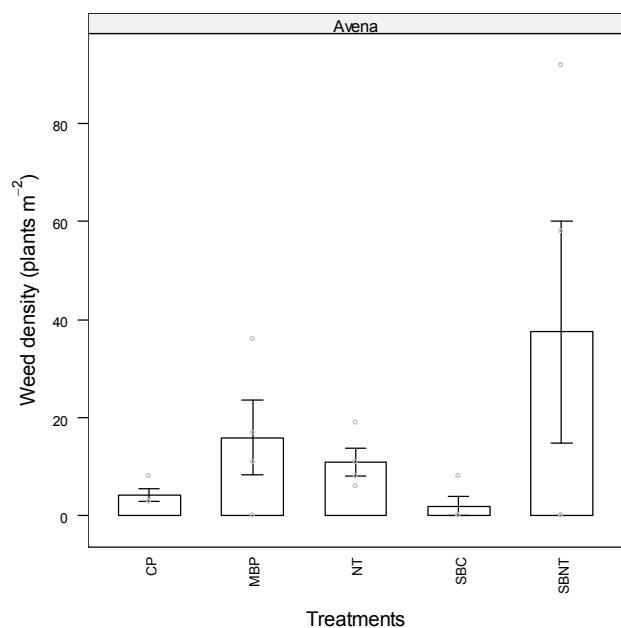


Figure 7.28 *Avena fatua* weed density before sowing/tillage in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Trifolium glomeratum seed banks and weed density

There was no *T. glomeratum* emergence in the field in 2004 (Figure 7.29) in any of the treatments and this reflects zero germinable seedbanks at the start of the season before performing sowing/tillage operations (Figure 7.30). Towards the end of the

season, before the flowering of weeds, except in the SBNT treatment, all the other treatments had germinable *T. glomeratum* seeds present with greatest being in the SBC and CP treatments presumably because of seed deposition but due to dormancy changes in the seed (Figure 7.30).

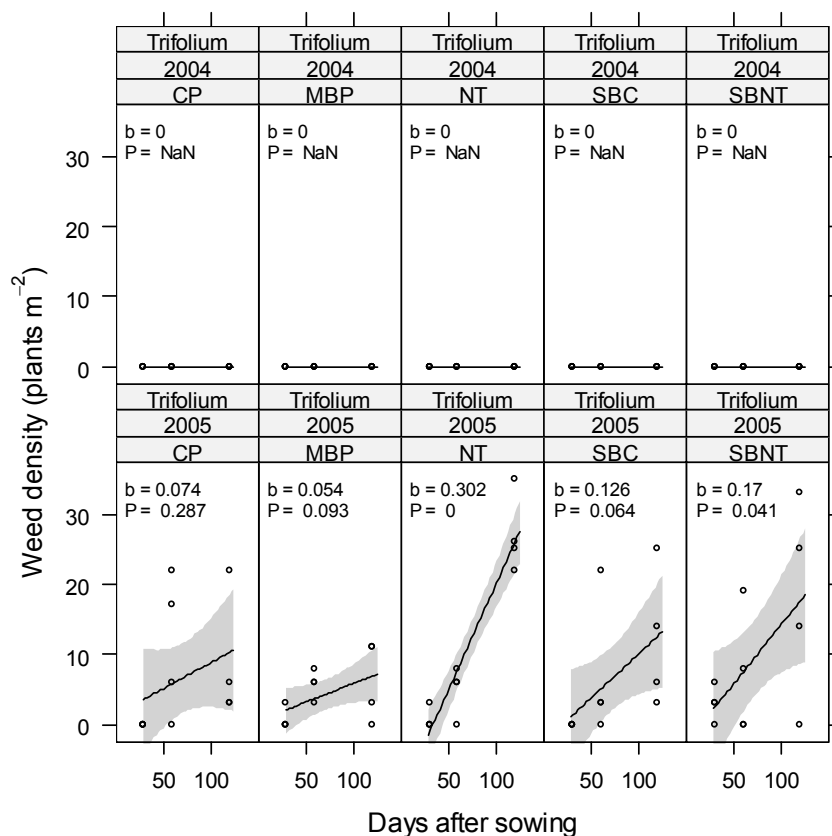


Figure 7.29 *Trifolium glomeratum* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. NaN= not applicable number (no emergence), b = the slope and P = significance of the slope.

In 2005, seedbanks of *T. glomeratum* were germinable, and CP was associated with the greatest density of *T. glomeratum* before the application of tillage, followed by SBNT with the lowest levels in NT (Figure 7.31). Seedlings emerged at all the sampling dates and the populations increased from 30 to 120 DAS (Figure 7.29). However, at 120 DAS the greatest density was observed in NT and SBNT and the lowest in MBP. The rate of increase was greatest in NT ($b=0.302$) followed by SBNT ($b=0.17$) and lowest in MBP ($b=0.054$). Because of variability in the data the increase was not always significant. There was no seedbank of *T. glomeratum* reported in any of the treatment plots at crop harvest in 2005 (Figure 7.30). This reflects that possibly that fresh seed of this species may be dormant.

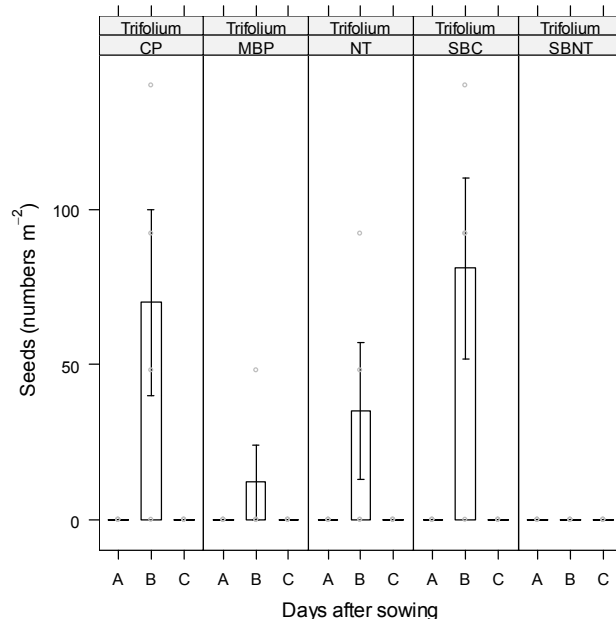


Figure 7.30 *Trifolium glomeratum* seedbank data at A= before sowing and tillage (2004), B= before flowering (2004) and C= before crop harvest but after seed drop (2005). The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

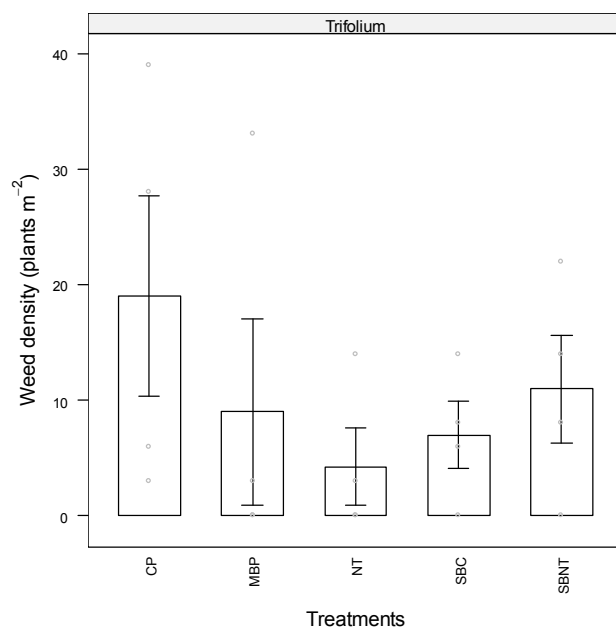


Figure 7.31 *Trifolium glomeratum* weed density before sowing/tillage in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Melilotus indica seed banks and weed density

Soil sampling conducted before the sowing/tillage treatments in 2004 revealed that all the three NT plots (NT, SBC and SBNT) had high numbers of germinable *M. indica* seeds whilst the CP and MBP treatments had very low numbers (Figure 7.32). Over

the sampling period from 30 to 120 DAS, there was little emergence with no significant differences between treatments. The population of *M. indica* decreased for all the treatments except CP from 30 to 120 DAS and the greatest density at 120 DAS was in CP with the lowest in MBP (Figure 7.33). Before flowering of *M. indica* in 2004 CP, MBP and NT showed zero seedbanks and SBC and SBNT had similar low numbers (Figure 7.32). A significant rate of decrease was reported only in the MBP treatment. There were no emergences of *M. indica* recorded in 2005 at any of the sampling dates; however, NT and SBNT had the largest seedbanks at harvest.

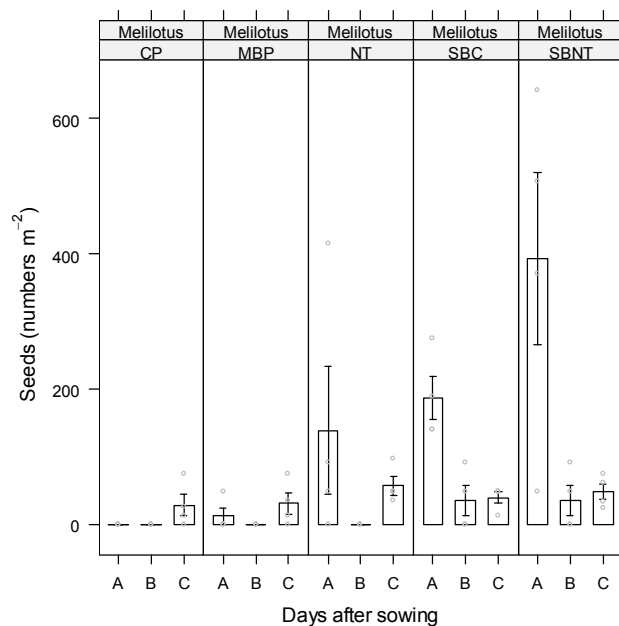


Figure 7.32 *Melilotus indica* seedbank data at A= before sowing and tillage (2004), B= before flowering (2004) and C= before crop harvest but after seed drop (2005). The vertical columns represent the mean values of individual treatment and the bars are the standard errors (\pm). Hollow circles represent the replicate value of each treatment.

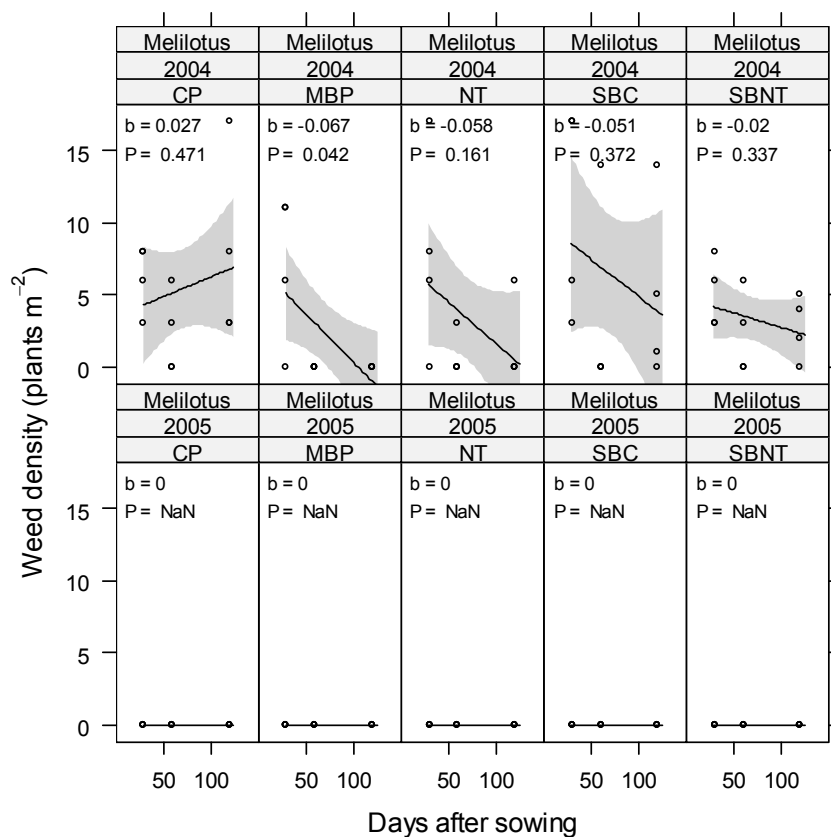


Figure 7.33 *Melilotus indica* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. NaN= not applicable number (no emergence), b = the slope and P = significance of the slope.

Portulaca oleracea seed banks and weed density

Chisel plough plots had the highest *P. oleracea* initial seedbank before sowing and tillage operations in 2004 followed by MBP and NT (data not shown). All the treatments had little emergence and there were no significant differences between any of the treatments at any of the sampling dates (30-120 DAS). Density generally increased in all the treatments over the sampling period except in CP (Figure 7.34). Whilst overall levels were relatively low, the rate of increase was largest in SBNT ($b=0.055$) in 2004 and there were nil seedbanks recorded before flowering of plants in 2004.

Portulaca oleracea did not emerge in any of the plots before tillage in 2005. Correspondingly, there was no *P. oleracea* after the application of treatments or at harvest in 2005.

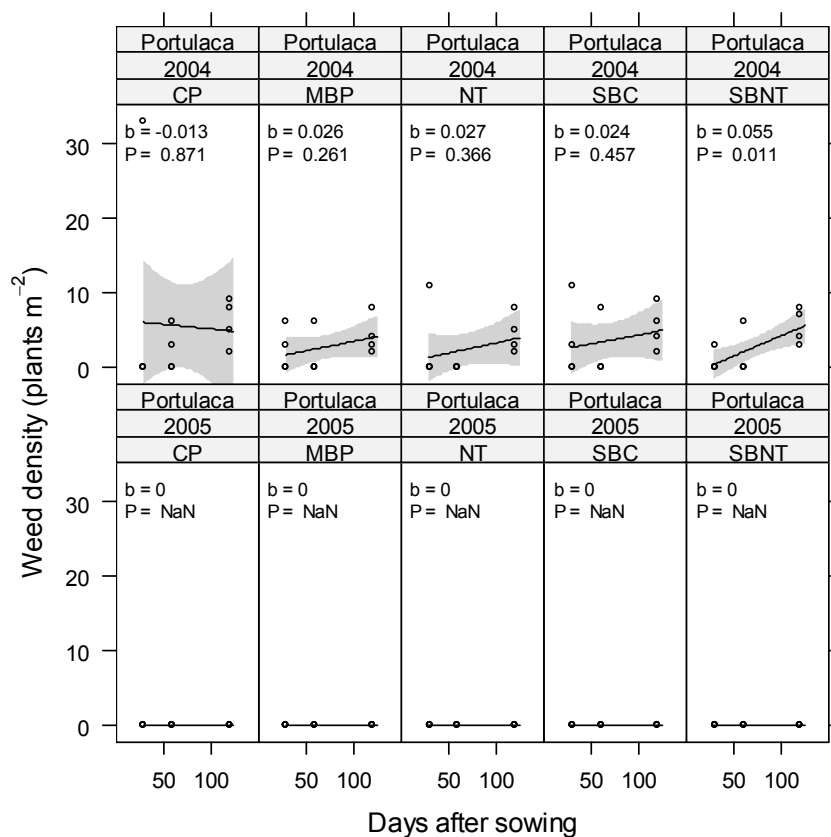


Figure 7.34 *Portulaca oleracea* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. NaN= not applicable number (no emergence), b = the slope and P = significance of the slope.

Lamium amplexicaule seed banks and weed density

There was no *L. amplexicaule* emergence in the field in 2004 (Figure 7.35) in any of the treatments and no germinable seedbanks at the start of the season (Figure 7.36). But towards the end of the season, before flowering of weeds, except in the MBP and CP treatments, the other treatments had germinable *L. amplexicaule* seeds present but the data were highly variable (Figure 7.36).

In 2005, the seedbank before the tillage/sowing operations was highest in NT treatment followed by SBNT with no *L. amplexicaule* in the MBP treatment (Figure 7.37). Few seedlings emerged in any of the treatment plots at 30 DAS; however, there were few emerging at 60 DAS. The population declined again before the harvest of the crop (Figure 7.35). The seedbank data at harvest was greatest in NT and SBC plots and lowest in MBP and CP (Figure 7.36).

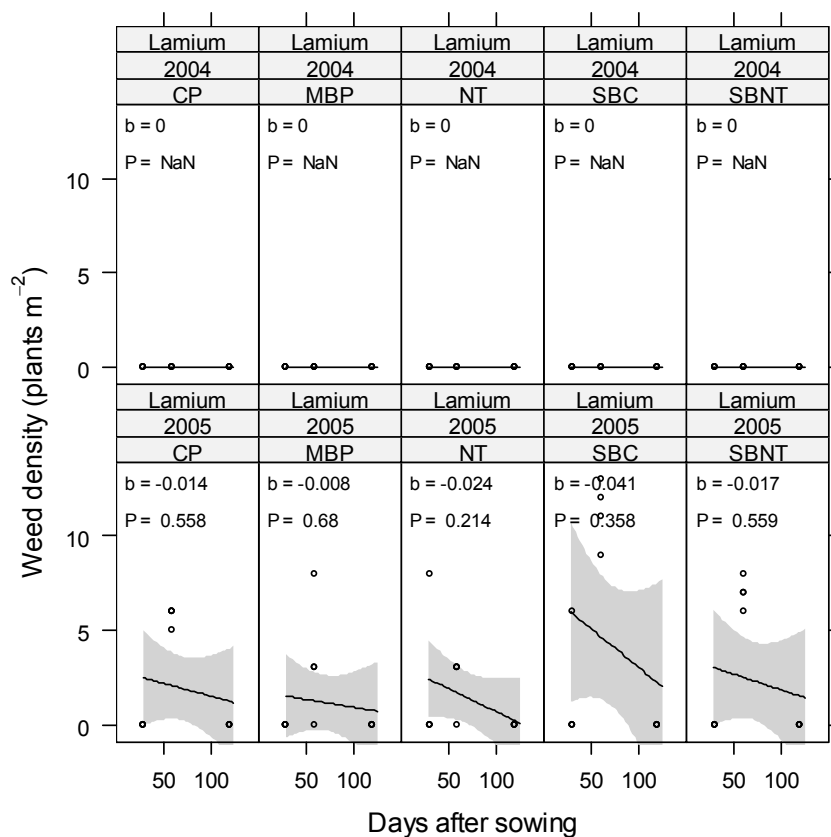


Figure 7.35 *Lamium amplexicaule* density at 30, 60 and 120 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. NaN= not applicable number (no emergence), b = the slope and P = significance of the slope.

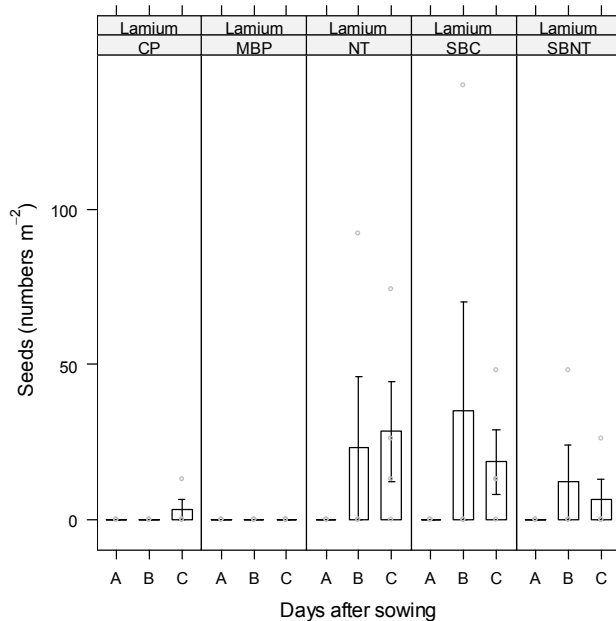


Figure 7.36 *Lamium amplexicaule* seedbank data at A= before sowing and tillage (2004), B= before flowering (2004) and C= before crop harvest but after seed drop (2005). The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

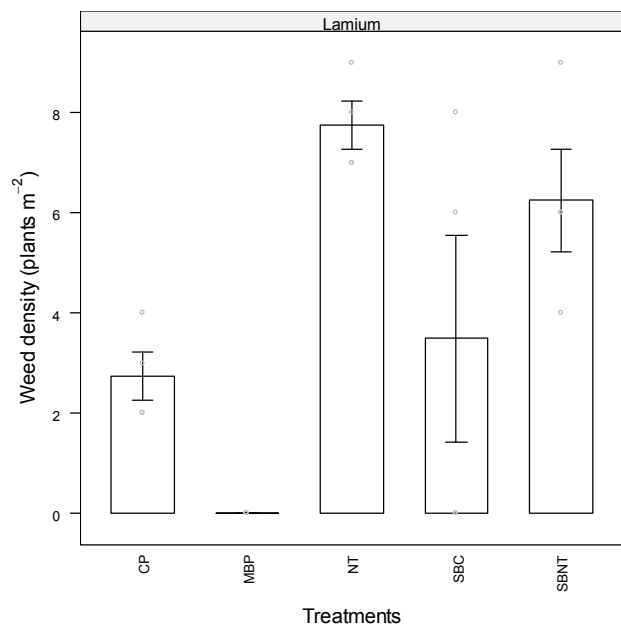


Figure 7.37 *Lamium amplexicaule* weed density before sowing/tillage in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Total weed biomass

Weed biomass was lowest in the MBP treatment in 2004 and this treatment also had the equal lowest weed biomass in 2005 though not significantly different to SBC. Conversely, the no-till treatments had the highest weed biomass in both seasons.

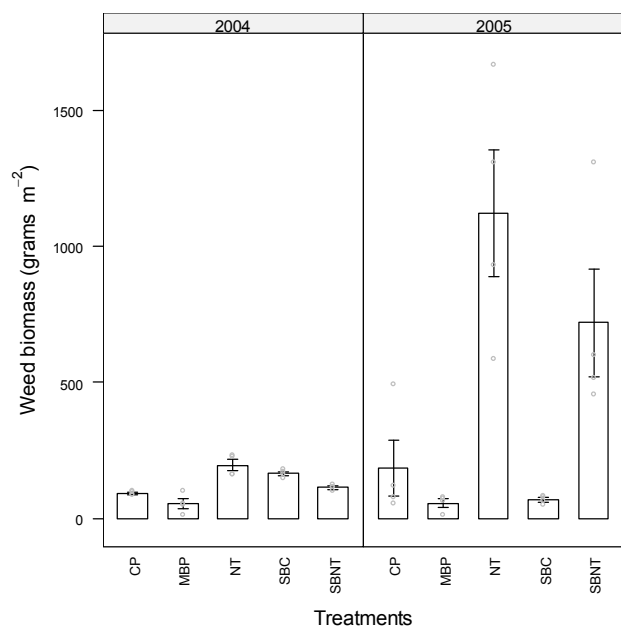


Figure 7.38 Weed biomass at harvest in 2004 and 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Crop tiller density

The ANOVA for the experiment showed that the three way interaction between days after sowing x treatment x year ($P= 0.530$) and the two way interaction of days after sowing x treatment ($P= 0.100$) were not significant. All the other two way interactions and the main terms were significant ($P\leq 0.01$) except the treatment main term which was not significant ($P= 0.205$)

Wheat tiller density across all the treatments in 2004 increased from 30 to 60 DAS (Figure 7.39). The tiller density at 30 DAS was not significantly different between treatments. At 60 DAS, the number of tillers (based on mean values) was highest in MBP followed by CP and lowest in NT. The rate of increase of tiller density was highest with MBP ($b= 12.65$) followed by CP ($b= 11.45$) and least in the no-till plots. Rate of change of tiller density over time was significant for all the treatment plots in 2004.

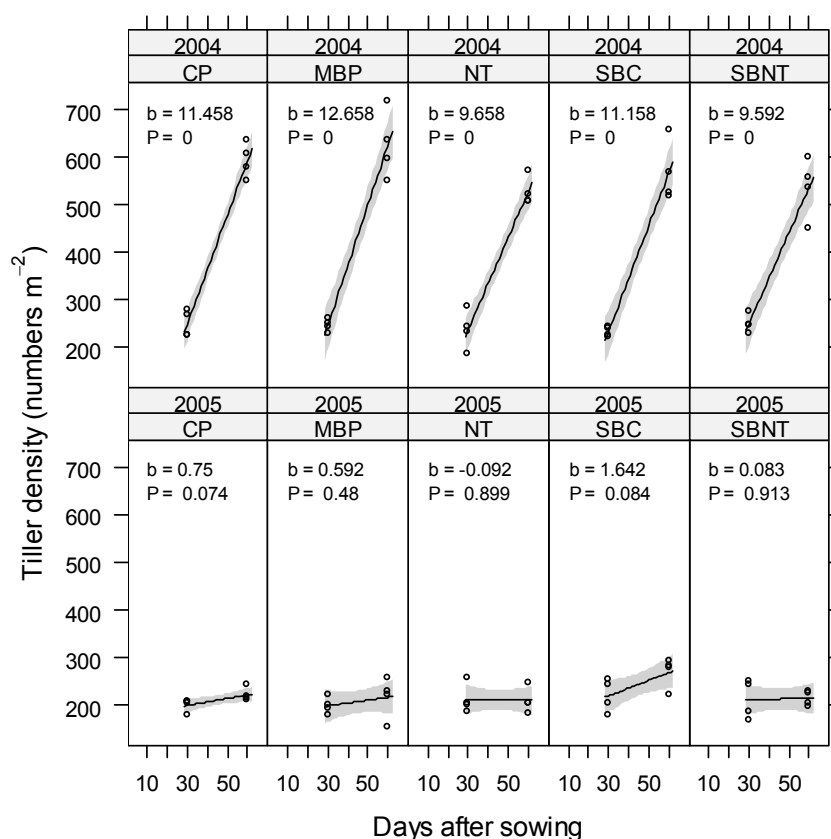


Figure 7.39 Tillers density at 30 and 60 DAS in 2004 and 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

In 2005 tiller density was greatly reduced in comparison with that in 2004. As in 2004, at 30 DAS, tiller density was not significantly different between the treatment plots (Figure 7.39). At 60 DAS, in 2005 the population of wheat crop increased in all the plots except the NT plot ($b = -0.092$) which was associated with slightly decreased tiller density. The lowest density was in NT and SBNT and the greatest in SBC treatments. Overall, the rate of increase in the tiller density of wheat crop among the treatments over time was greatest in SBC ($b = 1.642$) followed by CP ($b = 0.75$). The rate of increase or reduction was not significant in any of the treatments in 2005 ($P \geq 0.074$).

Wheat grain yield

Grain yield was negatively related to weed biomass. In 2004, maximum grain yield was in CP and MBP and in 2005 the highest grain yields were in MBP, CP and SBC. The no-till tillage treatments (SBNT and NT) had the equal lowest grain yields in 2005. Overall, the yields in 2005 were much less than in 2004 (Figure 7.40).

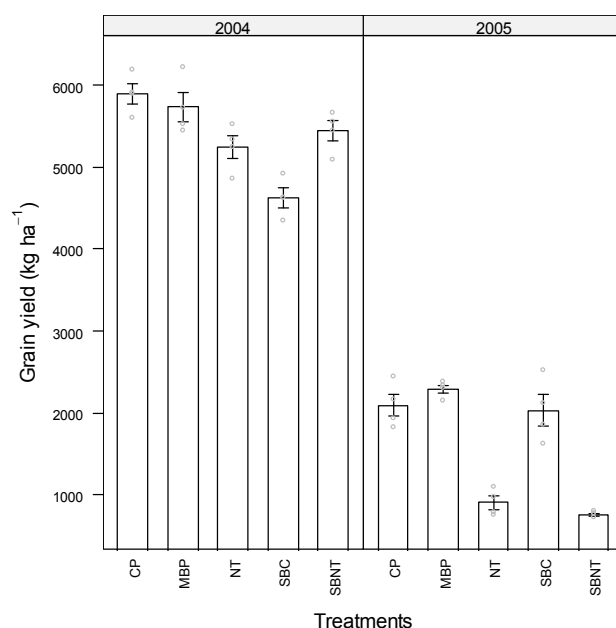


Figure 7.40 Grain yield (kg ha^{-1}) in 2004 and 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Grains per head

In 2004, there were no significant differences between treatments in grains per head (Figure 7.41). In the following year when there were fewer tillers m^{-2} the number of

grains head⁻¹ was higher. Mouldboard ploughing had significantly more grains head⁻¹ compared to SBNT.

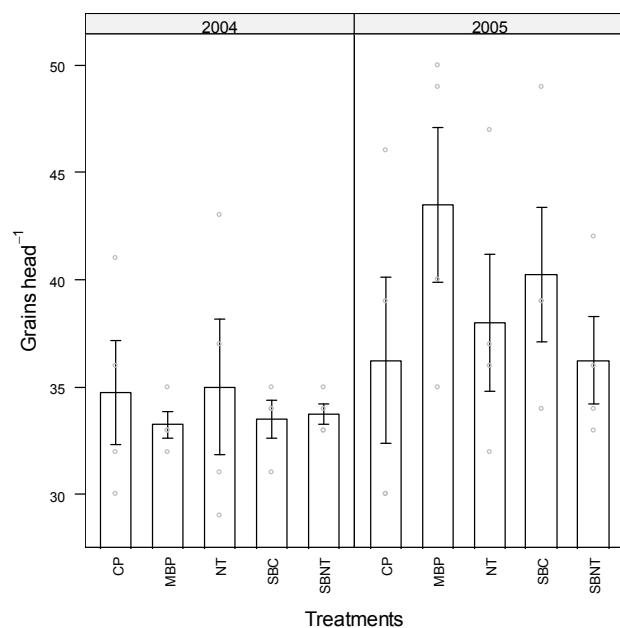


Figure 7.41 Grains head⁻¹ of wheat crop at harvest in 2004 and 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Thousand grain weight

In 2004 the greatest 1000 grain weight was observed in MBP followed by SBNT while the lowest was in the other two NT plots. In 2005, the greatest 1000 grain weight was associated with MBP and SBC and the lowest with NT (Figure 7.42).

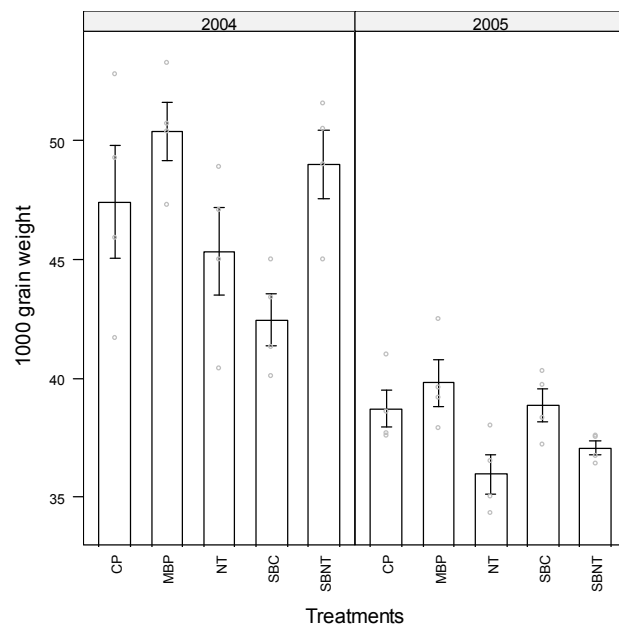


Figure 7.42 Thousand grain weight of wheat heads at harvest in 2004 and 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

***Lolium rigidum* experiment (Tamworth)**

The results from the germination and dormancy experiment initiated before the start of the experiment indicated that out of 50 glyphosate resistant *L. rigidum* seeds, 90 % seeds were germinable, 5 % seeds were viable but dormant and remaining 5 % were dead.

Weed density of *L. rigidum* over the 4 months sampling period in the Tamworth experiment in 2005 are presented in Figure 7.43. The ANOVA for *L. rigidum* density for the experiment indicated that the two way interaction between days after sowing x treatment and the treatment main terms were highly significant. Of the main terms, 'days after sowing' was not significant.

***Lolium rigidum* density in 2005**

In 2005, *L. rigidum* seedlings emerged early because of early rain. Seven days before tillage and sowing, *L. rigidum* density was significantly lower in the SBC and SBNT plots presumably due to burning effects and the non burnt treatments showed similar emergence (Figure 7.43). After burning, cultivation and sowing, numbers of *L. rigidum* plants dropped rapidly in all the treatments except the NT plots where the

numbers increased sharply. Most plants at 30 DAS were freshly germinated though there were small numbers that survived the tillage operation (Figure 7.44).

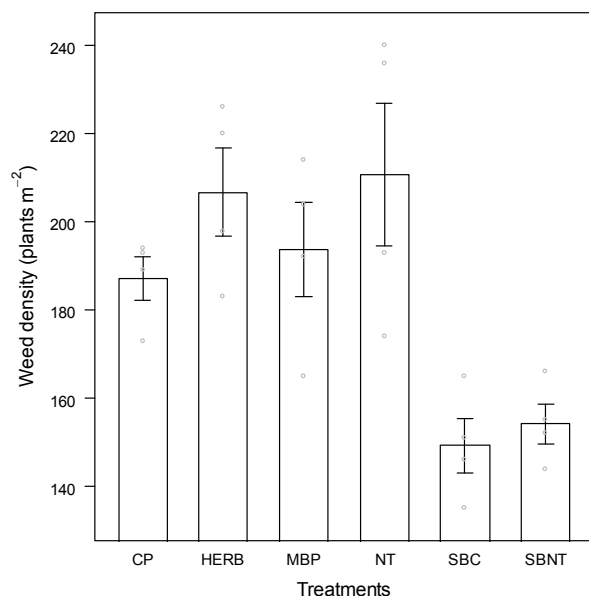


Figure 7.43 *Lolium rigidum* weed density 7 days before tillage treatments in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

In 2005, at 30 DAS, the highest *L. rigidum* density by far was in the NT treatments and SBNT had the second highest density (Figure 7.44). The lowest levels (based on the mean values) were in SBC and HERB treatments. *Lolium rigidum* plant density declined slightly in the NT, MBP and herbicide (HERB) treatments and increased slightly in the CP, SBC and SBNT over the sampling period (30-120 DAS). In general, the rate of reduction of *L. rigidum* density was greatest in NT ($b = -0.548$) followed by MBP ($b = -0.109$) and HERB ($b = -0.102$). The rate of change of *L. rigidum* density over time was not significant for CP and MBP.

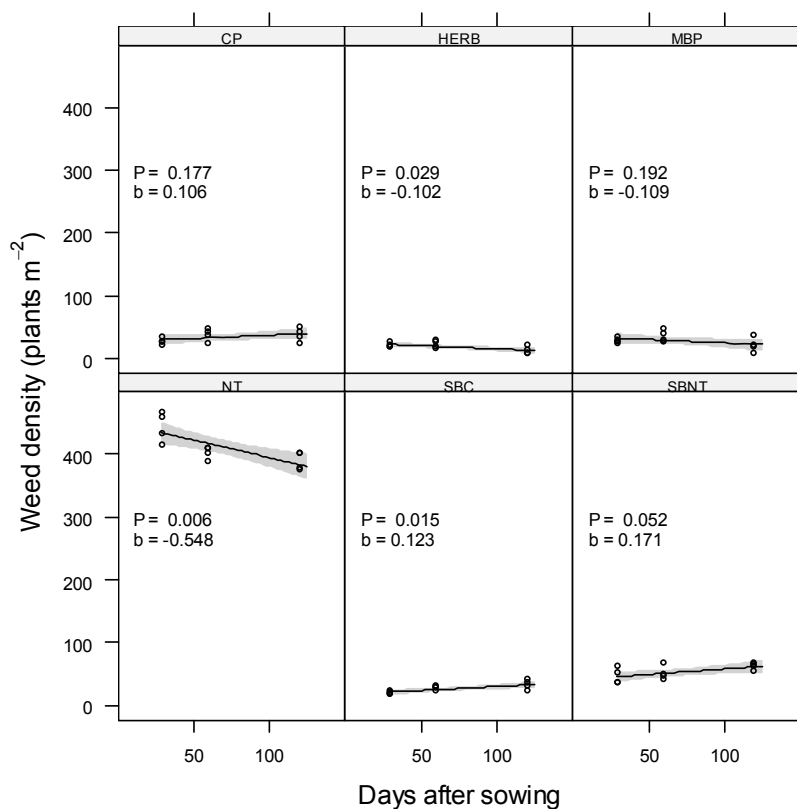


Figure 7.44 *Lolium rigidum* density at 30, 60 and 120 DAS in 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

Lolium rigidum density and seedbank in 2006.

The number of *L. rigidum* seedlings emerging in 2006 from the previous year's seed shed were generally very high ($> 1000 \text{ m}^{-2}$) but lowest in the MBP and HERB and greatest in the NT and SBNT treatments (Figure 7.45).

After the application of glyphosate at the 2-3 leaf weed stage, *L. rigidum* was again counted in October (spring). There were no new seedlings observed in any of the treatment plots. The straw burning with cultivation (SBC) treatment was the best in limiting the *L. rigidum* seedbank to less than 100 seeds m^{-2} followed by MBP, HERB and CP which limited the *L. rigidum* seedbank to under 200 seeds m^{-2} . Straw burning with no tillage (SBNT) had the highest seedbank of 484 m^{-2} followed by the NT treatment with 344 m^{-2} (Figure 7.46).

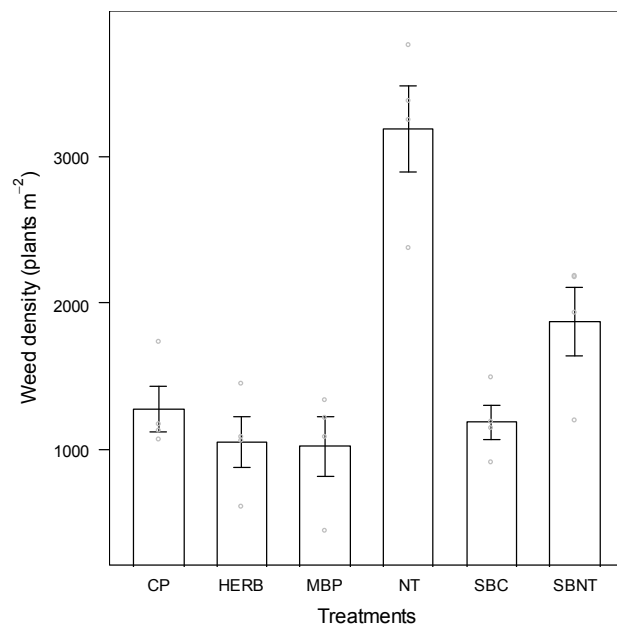


Figure 7.45 *Lolium rigidum* density in 2006 before glyphosate application. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

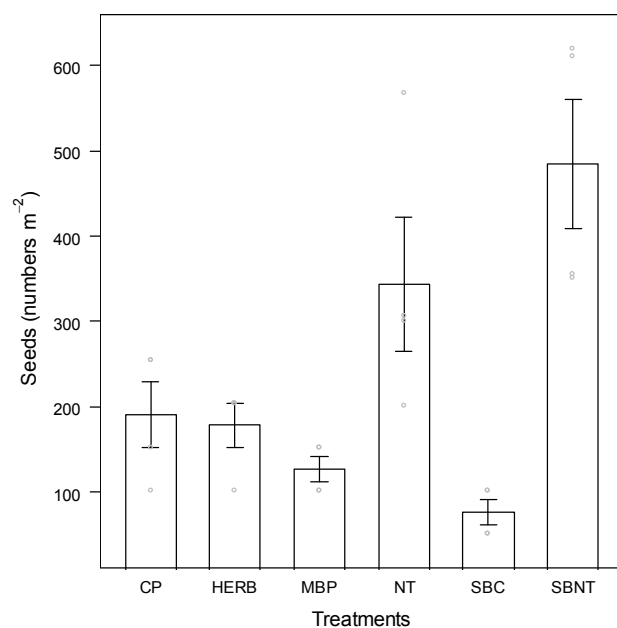


Figure 7.46 *Lolium rigidum* seedbank data in spring 2006. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

Crop tiller density

The ANOVA for crop tiller density indicated that the two way interaction between days after sowing x treatment ($P= 0.299$) was not significant. The days after sowing and treatment main terms were highly significant ($P < 0.001$).

Tiller density across all the treatments increased over the sampling period (Figure 7.47). The highest tiller density at 30 DAS was observed in the SBNT plots, and the lowest in CP plots (based on the mean values) however the treatment effects were not significant. At 60 DAS, the tiller population had increased in all the treatments with the greatest increase occurring in HERB followed by SBNT while the lowest density was in the MBP treatment. The rate of increase of tiller density was highest with HERB ($b = 4.283$) followed by SBC ($b = 3.367$) and least in the MBP treatment ($b = 2.217$). Rate of change of tiller density over time was significant for all the treatments.

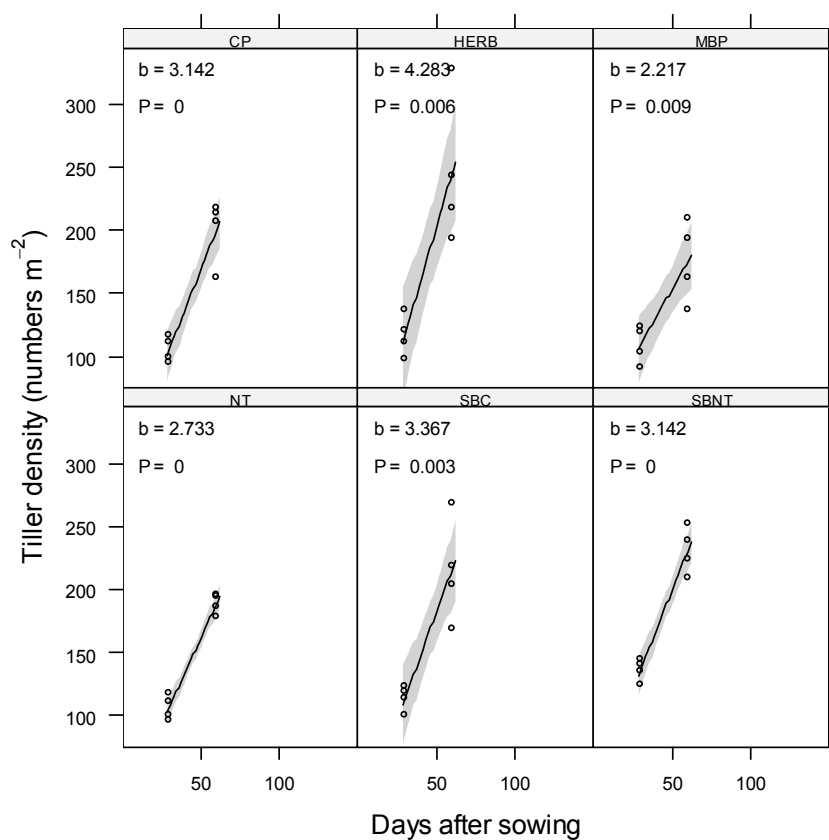


Figure 7.47 Wheat tiller density at 30 and 60 DAS in 2005. The shaded area represents the upper and lower 95% confidence intervals. Hollow circles represent the replicate values of each treatment. b = the slope and P = significance of the slope.

Wheat grain yield

Grain yield was similar and highest in the HERB and MBP treatments followed by SBC and CP and lowest in NT followed by SBNT (Figure 7.48).

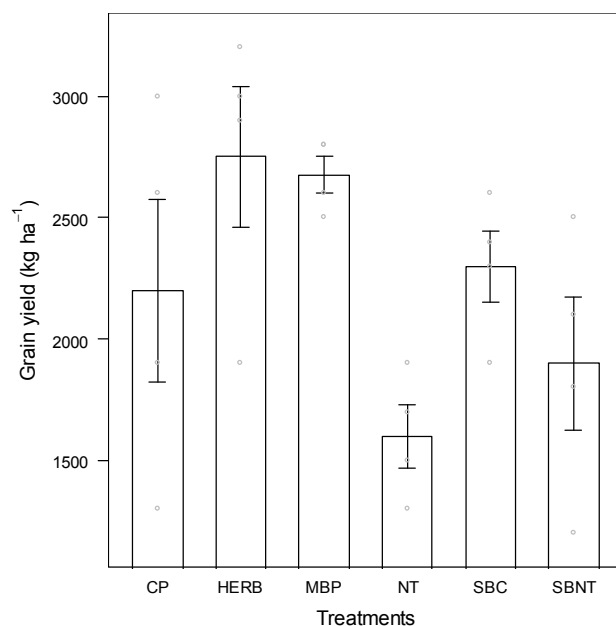


Figure 7.48 Grain yield (kg ha^{-1}) in 2005. The vertical columns represent the mean values of individual treatments and the bars are the standard errors (\pm). Hollow circles represent the replicate values of each treatment.

7.4. Discussion

Lolium rigidum experiment (Armidale)

The soil samples from 2004 and 2005 in the Armidale *L. rigidum* experiment had no germinations of *L. rigidum* seedlings. Seeds in the MBP treatment may have been buried beyond the range of the soil corer used for sampling. In the remaining no-till and CP plots, most *L. rigidum* seed is likely to have germinated as it was fresh seed that season, even though many seedlings may not have survived. Peltzer and Matson (2002a) indicated that some *L. rigidum* seed has been found to have up to 2-4 years dormancy but in one flush up to 70-80% of seeds are thought to be able to germinate. While it is likely that there was some proportion of *L. rigidum* seed in the soil samples which was dormant, the seed germination techniques used here for seedbank sampling may not have broken such dormancy. It is also possible that with low seedbank levels, the intensity of sampling may have been insufficient to detect the *L. rigidum* seed. It is also important to note that out of 1000 seeds m^{-2} incorporated by broadcast in each plot, only a maximum of 600 seeds m^{-2} managed to germinate in the NT plot. Dormancy of *L. rigidum* seeds may be one reason for low numbers appearing, however, some seed was lost while broadcasting on a windy day. The lower numbers in other treatments was probably as a result of tillage operations performed.

The seedbank data after harvest in 2005 showed that the seedbank was proportional to the low plant numbers in that season. Straw burning with cultivation best reduced the weed seedbank, probably due to the burning of straw (and possibly seeds) followed by light cultivation which would have helped destroy emerged and germinating *L. rigidum* seedlings. This led to lower *L. rigidum* plant numbers in the crop and subsequently lower shed seed numbers entering the soil seedbank. Chisel ploughing also reduced the number of *L. rigidum* plants and subsequent seedbank numbers followed by the MBP treatment plots. MBP plots had low weed density counts in the second year despite the possibility that the turning action of the MBP treatment may have returned some buried weed seeds to the soil surface. Chisel ploughing is likely to have buried some seeds in the soil and further killed others that had already germinated. No-till and SBNT plots were associated with large seed numbers lying on the surface which, without the application of a grass specific herbicide resulted in large infestations and elevated seedbank numbers. Although the weed density of SBNT plots was not higher at 120 DAS in 2005, the seed bank numbers after harvest in 2005 were very high probably because the *L. rigidum* seeds that survived burning had greater reproductive capacity. Similar results have been reported by Froud-Williams (1983a).

Disturbance of soil by tillage generally helped in reducing the above ground populations of *L. rigidum* in both years of the trial. In 2004, the effects were on seeds lying on the soil surface while in 2005, the effects of tillage were on both seeds and seedlings due to the early rains that prompted early *L. rigidum* emergence prior to tillage and sowing operations (Figure 1). MBP was best for *L. rigidum* suppression in 2004 and 2005. Froud-Williams (1983a) reported that ploughing to a depth of 20 cm eradicated *Bromus sterilis* and although buried seeds germinated they failed to emerge. Douglas and Peltzer (2004) also reported that MBP reduced the number of *L. rigidum* seedlings by over 95% compared with disk ploughing, full cut (complete soil disturbance with scarification) and no tillage systems. Seed burial by a mouldboard plough was the most effective annual ryegrass control treatment (Peltzer and Matson 2006). In Canada, Murphy *et al.* (2006) suggested that tillage had the largest effect on weed diversity and density. In our studies, NT promoted the highest weed density, CP was intermediate and MBP resulted in the lowest levels. Burning combined with

chisel ploughing gave an equivalent suppression of *L. rigidum* whereas chisel ploughing by itself was of intermediate value.

Straw burning can promote germination of seeds lying immediately beneath the burnt surface. Moss (1980a) reported that after straw burning the soil surface was a better environment for seed germination and seedling development. However, SBC in 2005 provided a substantial control of *L. rigidum* possibly due to burning of some of the seeds on the surface and burial of others. On the other hand, the SBNT plots appeared to provide the ideal environment for *L. rigidum* seed to germinate with seed remaining on the soil surface. Wilson and Cussans (1975) found that loss of dormancy of *A. fatua* seeds following burning resulted in more seedlings appearing in autumn. Where the stubble was cultivated, burning increased the number of seedlings by 250% and where it was not cultivated, by 330%. Also in our experiment, the SBC and SBNT plots did not receive any tillage during 2004 and the results obtained from SBC plots in 2005 suggest a very effective control even after just one year of burning and tillage.

The NT treatment had the highest *L. rigidum* numbers in 2004 and 2005. Likewise, Teasdale *et al.* (1991) reported that weed density increased after 1 year of no-tillage. Cardina and Herms (2002) also found higher seed densities in no-tillage compared with conventional tillage systems. In 2004, *L. rigidum* levels appeared to have little effect on grain yield of wheat, whereas in 2005, a wet year, there were severe reductions in yield particularly in no-till plots, which were also associated with higher *L. rigidum* numbers. The effect was clearly seen on tiller density both at 30 and 60 DAS which resulted in reduced grain yields. In 2004, the tiller density increased from 30 to 60 DAS whereas in 2005 due to the onset of rainfall and strong competition for space and nutrients by the *L. rigidum* and other emerging weeds, there was a large reduction in plant density from 30 to 60 DAS, except in the SBC plots which had increased tiller density due to less competition from *L. rigidum* plants. Furthermore, waterlogging associated with the heavy clay soils reduced the germination of wheat seedlings which resulted in strong competition from *L. rigidum* with its large number of tillers. Due to the lesser effect of *L. rigidum* in 2004, grains head⁻¹ of the wheat crop were not significantly different between treatments. However, in 2005 as a result of increased competition from *L. rigidum*, SBC and CP plots had significantly higher grains head⁻¹ followed by MBP. The effect of treatments on thousand grain weight in

2005 was not significant. It is also interesting to note that the grain yield under SBNT plots in 2005 was low compared with CP, MBP and SBC although SBNT plots had similar lower weed density as CP, MBP and SBC at 120 DAS. This may be related to antagonistic effects of burning under no-tillage as no such effects were seen under SBC. This effect reduced the number of crop tillers under SBNT plots which probably may have reduced the grain yield in 2005.

Other species experiment (Armidale)

Seedbank

In relation to the other species experiment at Armidale, results for seedbanks are discussed in order of their sampling in 2004 and 2005. The soil samples collected in 2004 before performing tillage treatments provided variable emergence counts for all the weeds. Tillage and sowing of the wheat crop markedly reduced the germinable seedbanks of *P. paradoxa* and *H. trionum* sampled at the end of the season before flowering of the weed plants. In the case of *H. trionum* most of the seeds in the seedbank appeared to be stimulated to germinate during the cropping cycle, which depleted the seedbank. However, for *P. paradoxa*, relatively few seedlings emerged in the crop possibly due to the relatively dry conditions (Figure 7.2) and the remaining seeds were not stimulated to emerge in the polyhouse, possibly due to dormancy mechanisms. In contrast, with higher rainfall in October and November 2005, *P. paradoxa* emerged late in the season in high numbers.

Polygonum aviculare and *A. fatua* seedbanks seemed to be less affected by tillage and sowing operations in 2004 as their numbers remained more or less unchanged. Like *P. paradoxa*, no seedlings of *A. fatua* emerged in 2004, and so the seedbank remained stable. In contrast, *P. aviculare* had seedlings emerge in the field but the soil seedbank appeared to be buffered against depletion. One possible explanation is that the seeds germinating under field conditions were of a different cohort with different germination and dormancy characteristics to those germinating in the polyhouse.

Lamium amplexicaule and *Trifolium glomeratum* had nil seedbanks in all the treatments at the initial sampling date in 2004 possibly because most of the seed were buried below 10 cm depth away from the soil corer or due to dormancy mechanisms. *Melilotus indica* and *Portulaca oleracea* had variable seedbank numbers across

treatments due to patchy distribution in the field. Tillage and sowing of the wheat crop markedly reduced the germinable seedbanks of *M. indica* and *P. oleracea* sampled at the end of the season before flowering of the weed plants. Dorado *et al.* (1999) found increased populations of the small-seeded *P. oleracea* under a NT system along with other weeds. In the present experiments, for both the weeds most of the seeds in the seedbank appeared to be stimulated to germinate during the cropping cycle, which depleted the seedbank. New seeds of *T. glomeratum* were observed in the treatment plots at the end of the season in 2004 probably due to release of dormancy in the case of NT plots and due to the turning action of CP and MBP implements in their respective plots.

Lamium amplexicaule seeds were also recorded in all the NT plots in 2004 at the end of the season possibly due to the release of dormancy. In 2005, with higher rainfall in October and November, seeds of *T. glomeratum* emerged late in the season in high numbers probably due to ideal environmental conditions for germination and release from dormancy. After harvesting, there were no seedbanks observed in any of the treatment plots possibly because *T. glomeratum* possesses an 'after ripening' period and so the seeds were dormant. *Portulaca oleracea* had no seed banks observed in 2005 because there were no emergences reported during the 2005 cropping period. There were very low numbers of seeds observed, which were either burnt, eaten by insects or buried deep in the soil by action of the tillage implements. In contrast, there were lower emergences of *M. indica* and *L. ampexicaule* in 2005. As a result, the seedbank data recorded after harvest remained more or less unchanged.

Interestingly, there were no seedbanks observed for any of the weed species in any of the treatment plots in 2005 before the flowering of weeds. The probable reason may be that before applying tillage treatments in 2005, a large proportion of the seedbank was exhausted by germination due to early rainfall at the ideal time for germination. The application of the burning and tillage treatments later possibly prompted most of the remaining seedbank to germinate and others to be buried in the MBP treatment. Some of the sampled seeds were unable to germinate due to dormancy mechanisms.

Above ground weeds

In general, the weed species examined responded differently to tillage types. For *P. aviculare*, *P. paradoxa*, *A. fatua* and *H. trionum*, the effects were on seeds lying on the soil surface in 2004 while in 2005, the effects of tillage were seen on both seeds and seedlings due to early rains and early weed emergence prior to tillage and sowing operations (Figure 7.2). MBP gave the greatest reduction for *P. aviculare* in both seasons whilst although statistically non-significant there appeared to be a similar suppression for *P. paradoxa* in both 2004 and 2005. In other work, the population of winter and summer annuals, including *Polygonum convolvulus*, increased in the soil seed bank as tillage was reduced (Donovan and Mc Andrew 2000).

In the present work, SBC in 2005 provided a substantial control of *P. aviculare* and *P. paradoxa* possibly due to burning some of the seeds on the surface and burying others. Straw burning with cultivation and MBP also provided good control of *A. fatua* and *H. trionum* up to 60 DAS in 2005 but possibly the late arrival of rains prompted the germination of some seeds later in these treatments. Wilson (1978) evaluated cultivations and found tine and MBP cultivations influenced the decline of *A. fatua* seed production.

Similar to the other weeds, the effects of tillage on *T. glomeratum*, *M. indica*, *L. amplexicaule* and *P. oleracea* were on seeds lying on the soil surface in 2004 while in 2005, the effects of tillage were seen on both seeds and seedlings due to early rains (Figure 7.4) and early weed emergence prior to tillage and sowing operations. Before applying tillage treatments in 2005, *L. amplexicaule* had its lowest weed density in MBP and its greatest in NT, possibly due to burying of seeds as a result of 2004 ploughing. The density of plants later in the cropping cycle was lower and similar for NT and MBP possibly because of tough competition from the crop, as the populations were lower at the initiation of the experiment in 2005. Barberi and Cascio (2001) found the highest weed density in NT plots and minimum in CP. Torresen *et al.* (2003) reported similar results in Norway.

There was no emergence of *M. indica* and *P. oleracea* in any of the treatment plots before the tillage operations in 2005 probably due to low density counts in 2004. The seeds shed in the treatment plots were exposed naturally in the field and later two

(SBC and SBNT) of the five treatments were straw burnt. In the cropping phase from 30 to 120 DAS, MBP was associated with the lowest density of *M. indica* due to burying the seed deep in the soil. Cardina *et al.* (1991) observed highest seed density of mixed weed species in no tillage and lowest in MBP plots due to better weed control in tillage treatments. *Portulaca oleracea* density during this period was similar and low in all the treatment plots possibly due to the low initial population before the start of the trial in 2004. The NT treatment was associated with the lowest *T. glomeratum* density followed by SBC and MBP but tillage operations largely affected this pattern. During the cropping cycle, after the tillage and sowing operation, weed density was observed to be lowest in MBP plots.

Weed biomass and yield attributing characters

In 2004, a combination of mixed weed flora in all treatment plots appeared to have relatively little effect on the grain yield of wheat, whereas in 2005, a wet year, there were severe reductions in yield particularly in NT treatments, which were also associated with higher weed biomass. Torresen *et al.* (2003) found that weed density increased and grain yield decreased with less intensive tillage compared with ploughed plots. Maximum and similar weed biomass in 2004 was found in NT and SBC treatments, originally considered as NT treatments. However in 2005, NT and SBNT treatments had the highest weed biomass and the lowest was in MBP and SBC possibly because MBP was able to bury a large proportion of seed in the soil and not many of those seeds were back on the surface after the second years ploughing. Straw burning with cultivation was associated with burning and burying a large proportion of seeds. Wilson and Cussans (1975) reported higher weed densities in cultivation followed by burning of the stubble. Furthermore, waterlogging associated with the heavy clay soils reduced the germination of wheat seedlings which resulted in strong competition from weeds. In 2005, MBP and SBC had the highest yields whereas NT and SBNT yielded poorly.

The effects of waterlogging on crop tiller density and resulting in reduced yields were similar to those discussed in the ryegrass experiment and were associated with heavy clay soils. In 2004, the tiller density increased from 30 to 60 DAS whereas, in 2005 due to onset of rainfall and strong competition for space and nutrient requirements by the weeds, tiller density declined from 30 to 60 DAS except in the SBC which had

increased crop density due to less competition from mixed weed flora. Due to lower competition from weeds in 2004, grains per head of the wheat crop were similar across all the treatments. Thousand grain weight was however affected by the treatments and MBP plots were associated with the highest thousand grain weight due to better weed control. However, in 2005 as a result of an increase in competition from weeds, MBP and SBC plots had significantly higher grains head⁻¹ and thousand grain weight. Straw burning with cultivation provided a substantial control of weeds possibly due to burning of some of the seeds on the surface and burial of others.

***Lolium rigidum* experiment (Tamworth)**

At Tamworth, tillage, burning and herbicide treatments all helped in reducing the number of *L. rigidum* in the first year. Straw burning and cultivation was best for *L. rigidum* suppression in 2005 followed by HERB. Certain *L. rigidum* populations have acquired resistance against diclofop-methyl (Hoegrass) across Australia; however, the plants emerging from the seed used in this study seemed to have nil or little resistance against this herbicide and so were easily managed. Broster and Pratley (2006) found in a survey of commercially available *L. rigidum* seed that 77% of samples tested were resistant to group AI (fop) herbicides. No-till plots had the highest *L. rigidum* numbers in 2005 followed by SBNT. The NT and SBNT plots appeared to provide the ideal environment for *L. rigidum* seed to germinate with seed remaining on the soil surface.

In 2006, the density of emerged *L. rigidum* seedlings before the application of glyphosate in all the plots was greatest in NT and SBNT and lowest in MBP and HERB. There was an indication that SBC had a higher *L. rigidum* density than the MBP but this was not at a significant level. The results obtained were possibly related to the previous year's treatment effects. Legere *et al.* (2005) reported the results of seedbank-plant relationships for weeds in spring barley/red clover cropping systems and found that for most species, plant density was correlated with either the previous or current year's seedbank. Later in the spring, the seedbank data showed that, proportional to low plant numbers in the previous season, SBC plots kept the seed bank levels significantly below 100 m⁻², probably due to the burning of straw (and possibly seeds) followed by light cultivation, which would have helped destroy emerged and germinating *L. rigidum* seedlings. This led to lower *L. rigidum* plant

numbers in the crop and subsequently lower shed seed numbers entering the soil seedbank. CP also reduced the number of *L. rigidum* plants and subsequent seedbank numbers, equivalent to HERB. Chisel ploughing is likely to have buried some seeds in the soil and further killed others that had already germinated. Although the weed density of SBNT plots was not higher at 120 DAS in 2005, the density observed before application of glyphosate in the next year was very high probably because the surviving *L. rigidum* seeds after burning had greater reproductive capacity.

Tiller density was not greatly affected as a result of the various levels of infestations in all the treatments. At 60 DAS it was highest under HERB plots probably due to minimum soil disturbance from tillage and efficient control from the applied herbicide. The wheat grain yield was not proportional to the decrease in *L. rigidum* density in individual plots. The greatest yield was in HERB possibly due to better weed control as a result of application of herbicide. NT and SBNT had the lowest yield in proportion to greater *L. rigidum* infestations.

The trials performed at Tamworth and Armidale varied from each other as the treatments were repeated the second year at Armidale but not at Tamworth. Overall, comparing the first year of both the experiments, the trend in reduction of *L. rigidum* density was similar for both the trials regardless of the differences in the climatic conditions. Generally, Armidale experienced greater average rainfall each month compared with Tamworth (Figures 5.1 and 5.2). In the absence of herbicide application, tillage and straw burning treatments drastically reduced the *L. rigidum* populations in the first year. Application of these similar treatments next year at Armidale confined the *L. rigidum* levels again to lower levels. At Tamworth, application of tillage and straw burning treatments in the first year were sufficient to reduce the populations to lower levels when later application of glyphosate in the following year stopped any further seed input into the system.

7.5. Conclusions

- *Lolium rigidum* has a relatively short lived seedbank which should enable exhaustion of the seedbank with control of HR plants over a period of 2-3 years. When faced with HR *L. rigidum*, SBC and MBP may provide farmers

with alternative non-chemical methods for control. In relation to other weeds, MBP favoured reduction of *P. aviculare*, *L. amplexicaule* and *M. indica*. Both SBC and MBP were able to reduce *Avena fatua*, *H. trionum* and *P. paradoxa* numbers equally, whereas *T. glomeratum* numbers were largely reduced with the NT treatment. While tillage in the form of CP or MBP demands greater resources and time and may be less desirable for soil conservation, it may only be required once every 3 or 4 years. With the time frame seeds buried deep by MBP and prevented from emerging would lose viability before seeds might be brought back to the surface through subsequent cultivation. Burning wheat straw in combination with CP is likely to provide better control than CP alone. Herbicide susceptible populations may also be successfully dealt with using an appropriate chemical like diclofop-methyl which provided substantial control of *L. rigidum* at Tamworth in the first year. Environmental concerns regarding burning restrict its use every year but this practice may be able to be incorporated in the system once in 3-4 years to keep the seedbanks low. More work is required to look at combinations of alternatives to herbicides such as tillage and straw burning for control of herbicide resistant weeds like *L. rigidum*, and other weeds having threat of acquiring resistance, since not all seedlings were killed or seed production prevented in the treatments imposed here.

Chapter 8. General conclusions

8.1. Introduction

This research related to the examination of factors affecting the seedbank dynamics of *Lolium rigidum* and other cropping weeds of northern NSW which, to date, has been very limited. This lack of knowledge of seedbank dynamics in turn has limited our ability to recommend alternative approaches for the control of glyphosate resistant *L. rigidum*. This project was undertaken to gain an improved understanding of the seedbank dynamics of *L. rigidum* (including glyphosate resistant *L. rigidum*) and other weeds at risk of developing resistance, their seed viability and dormancy characteristics and to examine modified management strategies for *L. rigidum* control in the northern NSW environment.

8.2. Research findings

Level of herbicide resistance

Seed of *L. rigidum* was collected from the property “The Point”, Tamarang on the Liverpool Plains south of Gunnedah, New South Wales, which was representative of glyphosate resistant *L. rigidum* in this area. The sample was tested specifically against glyphosate and also with a range of commonly used herbicides for *L. rigidum* control to evaluate the overall resistance level in this population. The *L. rigidum* seeds exhibited high levels of resistance against glyphosate (group M) but also against chlorsulfuron (group B), and diclofop-methyl and tralkoxydim (group A). This *L. rigidum* population can however, be controlled successfully with sulfometuron (group B) herbicide. It appears from the results that this population possesses both cross and multiple resistance.

A commercial seed sample of *L. rigidum* was tested for comparison purposes under the assumption that it would be susceptible to glyphosate. However, this sample also exhibited strong resistance to glyphosate as well as to other commonly used herbicides (Group A and B) including sulfometuron. The resistance levels in these populations against so many herbicides is a serious situation; commercial grain growers need to select herbicides for management of *L. rigidum* in northern cropping areas to which they are not resistant and are likely to have to employ non-chemical

techniques such as cultivation and burning as well as rotating herbicides. Pasture seed users purchasing *L. rigidum* seed also need to be aware of the resistance levels in these populations as this may spread to other areas with limited options for management. These levels of resistance in *L. rigidum* indicate an immediate need for further studies on the current resistance status of *L. rigidum* and other weeds with a likelihood of acquiring resistance in the Liverpool Plain region. In this study *L. rigidum* seeds were collected from only one property due to limitations of resources and time. However, it would be useful to collect populations from a range of properties to better understand resistance levels across the region for this important grain producing area of Australia.

Seedbank levels on the Liverpool Plains

Monitoring of the *L. rigidum* seedbanks was carried out for 3 years using field sites on the Liverpool Plains with the aim of exploring the changing status of *L. rigidum* and other weeds at risk of developing herbicide resistance. The results suggest that currently, on most of the properties, farmers are adopting strategies such as the alternating use of herbicides to keep the seedbank numbers of *L. rigidum* at low levels (<62 plants m⁻²). However, high numbers of plants emerging on some properties suggested that farmers need to target the management strategies for *L. rigidum* and to assess the changing numbers. The greatest *L. rigidum* numbers were found in the top 0-2 cm of soil which may affect their longevity and emergence patterns. This knowledge can also be useful if monitoring of these seedbanks under longer term experimental work could be undertaken using differing control options to assess their relative success in reducing seed bank populations.

Polygonum aviculare and *S. oleraceus* with variable numbers across properties stand at risk of acquiring resistance to herbicides and so need to be controlled with alternative management systems. *Crassula colorata* and *L. amplexicaule* numbers, though at relatively low levels may pose a risk of increasing populations in future if adequate control measures are not implemented.

The seedbank species remained relatively unchanged over the 3 years of the present management systems. While there were few numbers of many species persisting

through the three years, levels in individual years were sufficient to compete with crops and so require ongoing attention.

Seedbank levels were determined by germinating seeds under polyhouse conditions. However, this germination technique only accounted for seeds which were not dormant at the time of germination in the polyhouse. The seed extraction technique under laboratory conditions could have provided total seedbank numbers, and if germination tests were also done, germinability as well. Nevertheless, for a species such as *L. rigidum* with relatively low dormancy levels, the method used was the most efficient.

Longevity and seedling emergence

In the short term (several months), factors such as soil type, rainfall and depth of burial affected the fate and condition of *L. rigidum* seeds and emergence pattern of seedlings. However, seeds experiencing either summer or winter dominant rainfall under polyhouse conditions lost their viability after 16 months of burial; likewise, under field conditions seed viability was lost within 15 months of burial on the Liverpool Plains. Seed burial did not extend seed longevity appreciably. Hence in the longer term *L. rigidum* behaviour in this summer dominant rainfall environment is likely to be similar to that in the southern Mediterranean climate regions of Australia.

Maximum emergence in the polyhouse occurred during mid autumn in the 18 to 20°C temperature range. Under field conditions, *L. rigidum* seeds germinated faster with rainfall and lost more than 90% of dormancy within first 6 months of burial. Knowledge from these trials will allow researchers to develop management strategies which may enhance the depletion of *L. rigidum* seeds in the shortest possible time e.g. by altering the cropping practices that may favour reduced levels of *L. rigidum* survival, adopting alternate management practices which may bury the seed long enough to deteriorate and die (as discussed in Chapter 7) or stopping *L. rigidum* seed production for at least 18-24 months to deplete the seedbank to zero.

In these experiments the *L. rigidum* seeds were placed in fine mesh nylon bags, so it was possible that some seeds germinated but were unable to emerge from the bags. The results therefore may have underestimated slightly *L. rigidum* emergence. Also,

the polyhouse experiment could not be started exactly when the seed of *L. rigidum* would naturally be dropped from the parent plant (December or January) but was rather initiated in March. This meant that the principal influence on seed dynamics soon after burial of *L. rigidum* was a dry autumn and winter for Tamworth conditions and wet Hamilton conditions.

Seedling emergence and WEEDEM

The emergence of herbicide resistant *L. rigidum* seed from Liverpool Plains and *L. rigidum* seed originating from Victoria was correlated in northern NSW with the WEEDEM (seed emergence) model developed in Western Australia. The emergence of *L. rigidum* seed from Victoria, which was assumed to be herbicide susceptible but found to be resistant to a range of herbicides (Chapter 3), was faster than HR seed from the Liverpool Plains. This difference could be due to differences in environmental conditions in which the seed populations matured or due to differences in the biotypes of *L. rigidum* used in addition to differences in herbicide resistance. Nevertheless, the majority of *L. rigidum* seeds emerged within 2-3 weeks of sowing in a cultivated field.

The predicted emergence by the WEEDEM model based on prevailing climatic and soil data for Armidale was faster by about 1 week than the actual emergences observed in the field most probably because WEEDEM predicts *L. rigidum* emergence for seeds germinating on the soil surface under no-till conditions. However, it may be assumed that predictions made for no-till conditions are likely to have been accurate for our conditions and should be equally applicable for other parts of NSW. Assuming that this model can be further developed to predict emergence under cultivated conditions as well as no-till conditions, farmers can be advised of the likely times and rates of emergence of *L. rigidum* in advance and this would help plant management operations. For example, if WEEDEM predicts the emergence of *L. rigidum* near to the time of sowing, farmers may delay the crop sowing date and choose to spray the field with a non-glyphosate herbicide or cultivate after most of the *L. rigidum* has emerged. These predictions would provide the farmers with greater flexibility with *L. rigidum* control. Also, in the future, WEEDEM should not only be calibrated using seed carried over from the previous season (unlike these trials) but, as

these results show, the model may also need to be calibrated with the local *L. rigidum* biotypes for most accurate emergence predictions.

Management

The alternative management strategies to herbicides investigated in this thesis helped in decreasing or at least restricting the seedbanks and plant populations of *L. rigidum* and other naturally growing weeds. *Lolium rigidum* was found to have low dormancy in cropping situations and this should enable farmers to lower seedbank levels within a short timeframe. Straw burning with chisel ploughing and MBP provided substantial control of *L. rigidum*, *A. fatua*, *H. trionum* and *P. paradoxa*. *Polygonum aviculare*, *L. amplexicaule* and *M. indica* responded better to MBP, while *P. paradoxa* showed the greatest reductions with SBC. One year of MBP and SBC alone helped in reducing the numbers of weeds to low levels. Considering the beneficial effects, efforts could be made to incorporate these management strategies into the cropping system when herbicide resistant populations reappear or at least once in 3-4 years as a preventive strategy to control development of herbicide resistance. Other cultivation options, such as disc ploughing and scarifying, which perform a similar function to MBP may be useful in achieving similar results.

Diclofop-methyl was found to provide useful control of herbicide susceptible *L. rigidum* populations at Tamworth. Sulfometuron may also be an option to manage glyphosate resistant *L. rigidum* as suggested in Chapter 3. Both the management experiments performed at Armidale had tillage treatments which were planned to be followed for 2 years. But, because there was no carryover wheat straw in 2004, the burning treatments were not initiated at that time. It would have been good to have repeated the experiment for one more year to provide more information about the behaviour of *L. rigidum* under burning but restrictions on the project meant that there was insufficient time. Soil sampling of seedbanks could not be done before initiating burning treatments in 2005 due to continuous rainfall during that month and a heavy clay soil. An estimate of initial seedbanks at this stage could have provided us with a better understanding of the treatments effect on weed seedbanks.

8.3. Future research

Populations of *L. rigidum* exhibiting resistance to one or more herbicides should be collected from a range of properties in the Liverpool Plains area of New South Wales to gain a better knowledge of current trends of resistance problems that farmers are facing and so that future research can be directed accordingly.

Currently, some properties on the Liverpool Plains appear to have large populations of glyphosate resistant *L. rigidum*. It is therefore suggested that the characterisation and monitoring work should be carried on each year to gather knowledge about the changing patterns of populations. It would also be useful as the number of farms with glyphosate resistant *L. rigidum* increases and there is a larger pool from which to choose, to set up a structured comparison of farmers' fields at various locations of known rotations. This would allow better interpretation in relation to reasons (cultivation, herbicides, crop rotations and edaphic or environmental factors) for the changing status of seedbanks over time.

Weed seed viability, germination, dormancy and seedling emergence are also greatly influenced by temperature and light intensity variations. Short term experiments with different temperature and light intensity ranges in growth chambers would be useful to gather information related to loss of viability, dormancy and germination and emergence characteristics of the seed simulating various cropping situations in Australia.

The WEEDDEM model should also be tested and calibrated for both no-till and tilled conditions in order to be relevant to where farmers are required to cultivate their fields to control herbicide resistant *L. rigidum*. Farmers should then be advised about the benefits involved with the use of WEEDDEM, and how they could plan sowing, cultivation, burning and herbicide spray operations according to predicted weed emergence.

Tillage and burning strategies, as alternatives to herbicides, provided adequate control of weeds. A variety of modified tillage operations either alone or coupled with burning could provide better and longer lasting control of herbicide resistant weeds.

Long term experiments should be planned which involve different crop rotations and one year of either of these treatments followed by 3-4 years of no-tillage with regular observations on changing seedbanks. The experiments should have separate treatments for herbicide resistant and susceptible seeds, to observe the behaviour of these seed samples against various tillage and burning treatments.

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Appendix

Publications arising from this thesis

- Narwal, S., Sindel B. M. and Jessop R. S. (2006). Tillage and residue burning affects weed populations and seed banks *In* "International Symposium on Crop Protection" p 94, 23rd May, 2006, University of Gent, Gent, Belgium.
- Narwal, S., Sindel B. M. and Jessop R. S. (2006). Effects of tillage and burning of residue on annual ryegrass (*Lolium rigidum* Gaud.) seed banks. *In* "NJF Seminar 378. Tillage systems for the benefit of agriculture and the environment" p 18, 29-31 May 2006, Nordiac Agriculture Academy, Odense, Denmark. NJF Report Vol 2 Nr 4.
- Narwal, S., Sindel B. M. and Jessop R. S. (2006). Weed seedbank changes for annual ryegrass (*Lolium rigidum*) and other species under a range of farm management practices on the Liverpool Plains of Northern New South Wales. *In* "Fifteenth Australian Weed Conference" (C. Preston, J. H. Watts and N. D. Crossman, eds.), pp 379-382, 24-28 September 2006, Adelaide, Australia.
- Narwal, S., Sindel B. M. and Jessop R. S. (2006). Tillage and residue burning affects weed populations and seed banks. *Communications in Applied Biology and Science* **71 (3a)**, 715-723.